B Physics at the Tevatron and the *B* Factories

$\sin 2\beta$ and B_s Mixing

Lecture II

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Overview

Motivation and History

- Why is *CP* violation interesting?
- First important *B* physics measurements

Introduction to the Experimental Setup

- *b* production mechanisms as motivation
- *B* Factories versus Tevatron
- BaBar/Belle versus CDF/DØ

Two Stories into some Detail

- Tools for the measurement
- Observation of *CP* violation in *B* systems, $\sin 2\beta$
- How Tevatron will measure B_s mixing, Δm_s

Web Pointers

The experiments

- Tevatron: http://www-cdf.fnal.gov/, http://www-d0.fnal.gov/
- *B* Factories: http://www.slac.stanford.edu/BFROOT, http://belle.kek.jp/

Overview reports

- The BaBar Physics Book

  http://www.slac.stanford.edu/pubs/slacreports/slac-r-504.html
- *B* Physics at the Tevatron: Run II and Beyond

  http://arXiv.org/pdf/hep-ph/0201071

Excellent live videos / transparencies on the Web

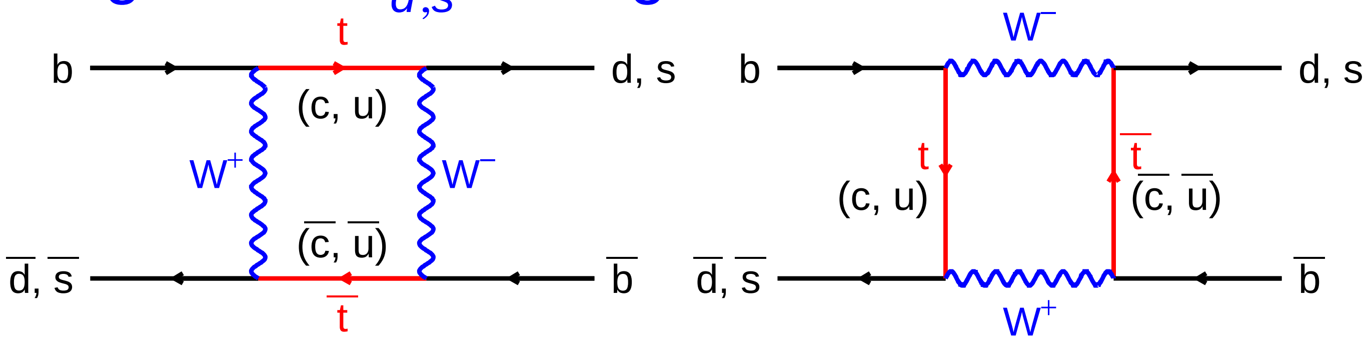
- SLAC summer school 2002:

  http://www-conf.slac.stanford.edu/ssi/2002/
- MIT Course: Heavy Flavor Physics (F. Würthwein)

  http://mit.fnal.gov/ ˜ fkw/teaching/mit8.881.html

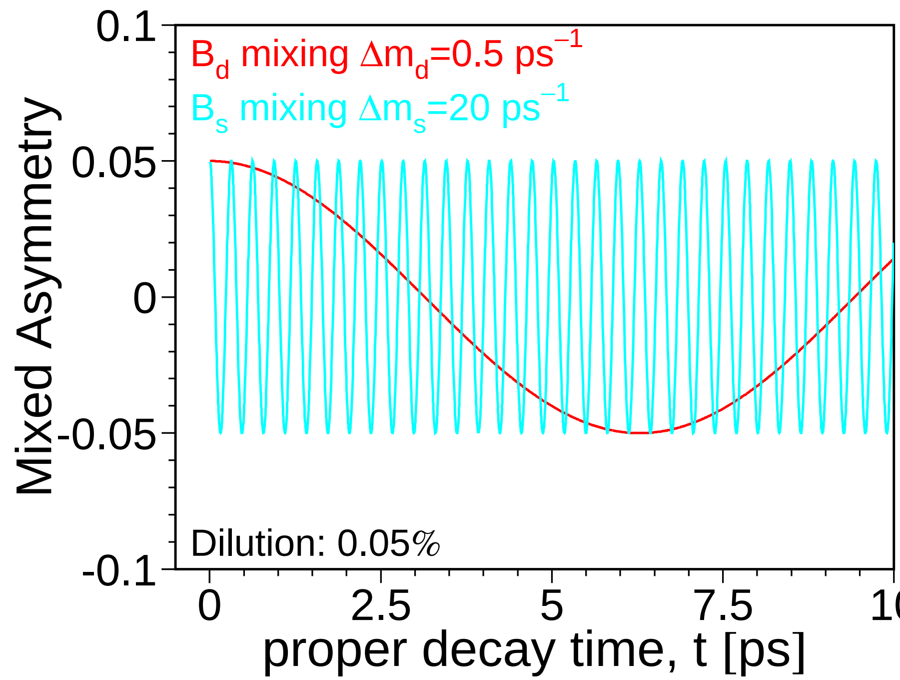
Advanced Measurements: B_s Mixing

Feynman diagram of $B^0_{d,s}$ mixing:



Differences

- + B^0_d crosses two families
- + B^0_s crosses one family
- + faster B^0_s mixing (≈ 40)



Experimental challenge

- + ct resolution critical
- + fully hadronic decays:

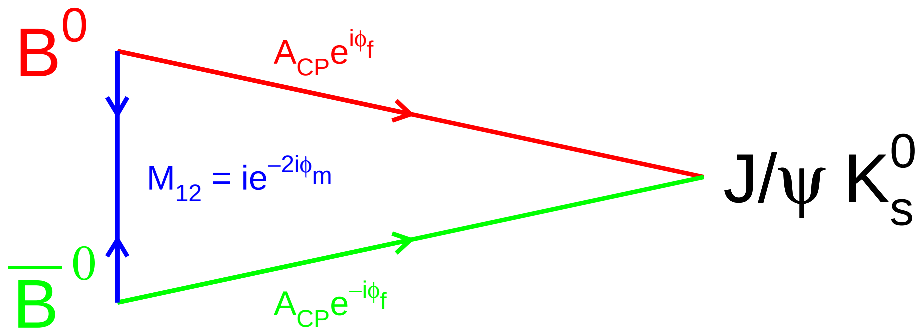
$$B_s \to D_s^- \pi^+ (\pi^+ \pi^-)$$

To be done at Tevatron

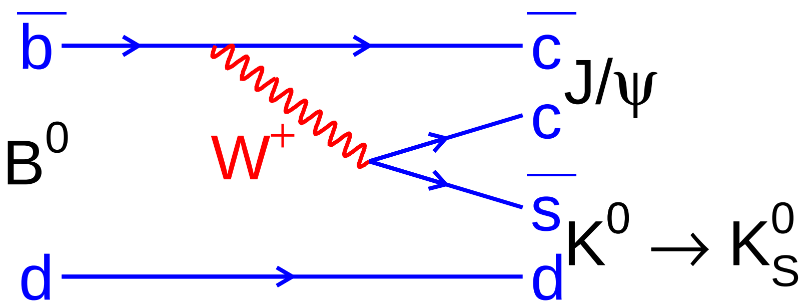
Advanced Measurements: *CP* Violation – $\sin 2\beta$

CP Violation mechanisms

+ interference of decay amplitudes
+ interference of mixing diagram
+ interference betwwen mixing and decay amplitude



Golden mode: $B^0 \to J/\psi K_S$



CP eigenstate: $\eta_{f_{CP}} = -1$

$$\begin{aligned} Im\lambda_{b\to c\bar{c}s} &= \eta_{f_{CP}}\, Im\left[\frac{V_{tb}V^*_{td}}{V^*_{tb}V_{td}}\,\frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}}\,\frac{V^*_{cd}V_{cs}}{V_{cd}V^*_{cs}}\right] \\ &= \eta_{f_{CP}}\sin 2\beta \end{aligned}$$

$$A_{f_{CP}}(t) = \frac{\Gamma(\overline{B}^0(t)\to f_{CP}) - \Gamma(B^0(t)\to f_{CP})}{\Gamma(\overline{B}^0(t)\to f_{CP}) + \Gamma(B^0(t)\to f_{CP})} = -Im\lambda_{f_{CP}}\sin\Delta m_d t$$

CKM Measurements from *B*

Unitarity triangle and what measures it

CP Violation parameter, $\sin 2\beta$

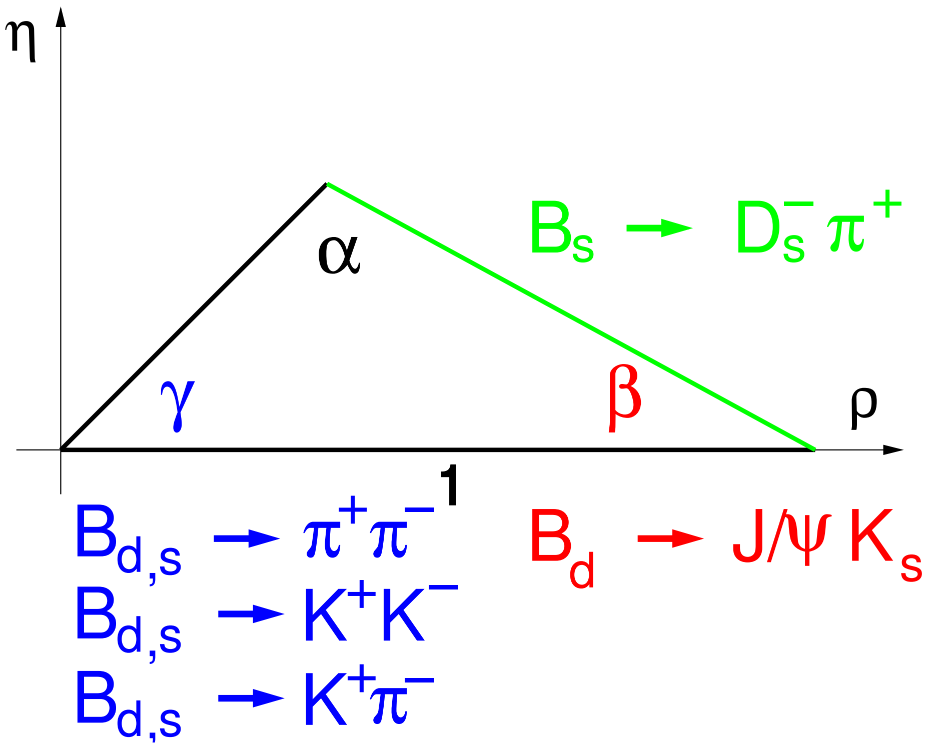
- $B^0 \rightarrow J/\psi K_S$
- simple signature
- relatively large branching

Mixing parameter, Δm_s

- $B^0_s \rightarrow D^-_s \pi^+$
- needs hadronic trigger
- clean signature
- relatively large branching

CP Violation parameter, γ

- $B^0_{s,d} \rightarrow \pi\pi, K\pi, KK$
- tricky.. for later



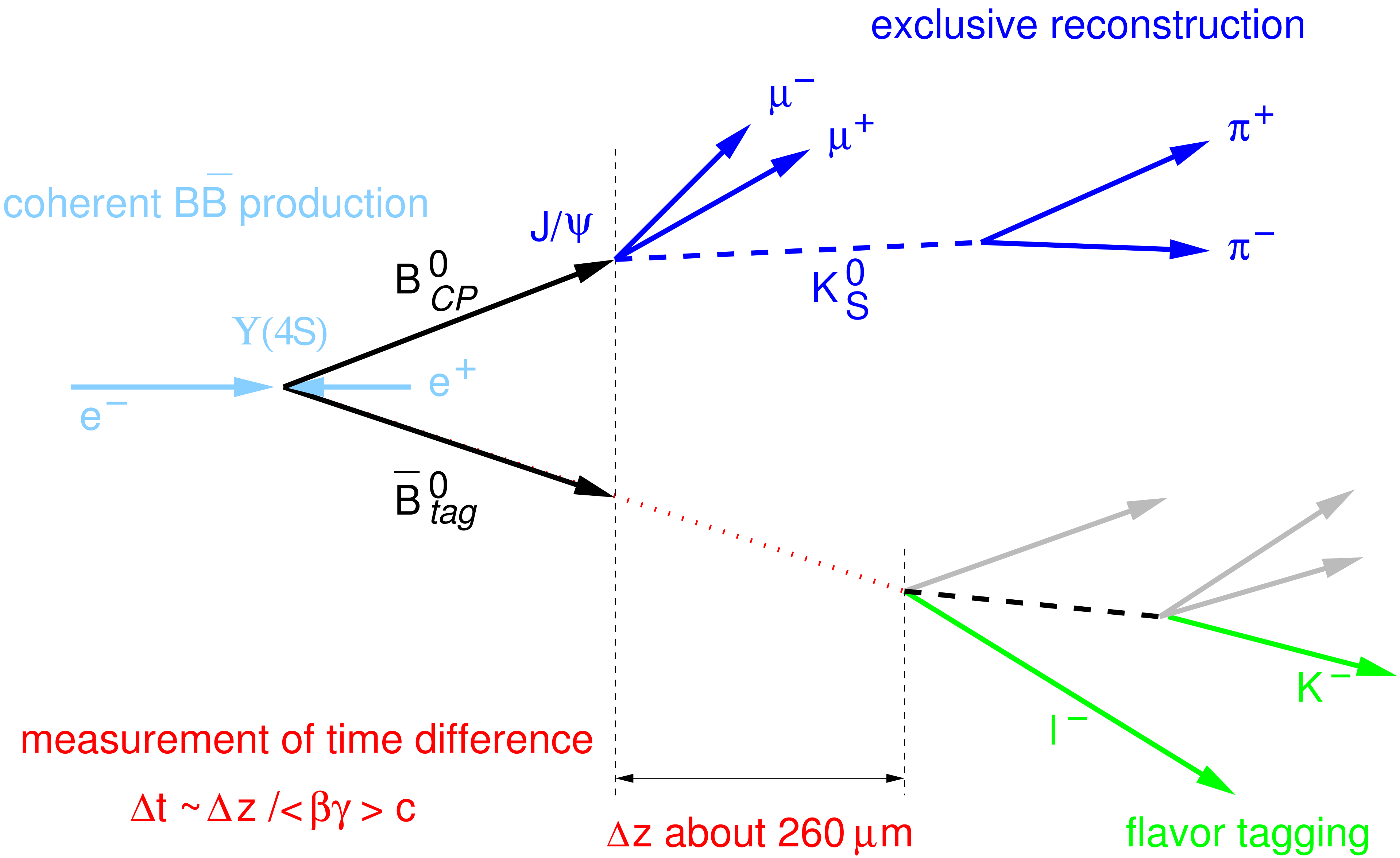
Comparisons of B Experiments

Accelerator	CESR,DORIS	LEP,SLC	PEPII,KEKB	Tevatron
Detector	Argus,CLEO	ADLO,SLD	BaBar,Belle	CDF,DØ
$\sigma(b\overline{b})$	$\approx$ 1 nb	$\approx$ 6 nb	$\approx$ 1 nb	$\approx$ 50 μb
$\sigma(b\overline{b}) : \sigma(had)$	0.26	0.22	0.26	0.001
b hadrons	B^0, B^+	all	B^0, B^+	all
Boost $< \beta\gamma >$	0.06	6	$\approx$ 0.5	2-4
Production	Bs at rest	$b\overline{b}$ btb	forward boost	$b\overline{b}$ not btb
Event pile-up	no	no	no	yes
Trigger	inclusive	inclusive	inclusive	selective

Comments

+ experimentally LEP/SLC at Z looks ideal – but expensive
+ Babar and Belle can cheaply produce although not all
+ Tevatron has the highest cross section and can do all but lots of background
+ nice complementary setup

Detailed Cartoon of Measurement at $\Upsilon(4S)$



Analysis Components

Final State Reconstruction

Measurement of t or Δt

b Flavor Tagging

Final State Reconstruction

Main B Reconstruction Variables – $\Upsilon(4S)$

In $\Upsilon(4S)$ rest frame:

E^*_{beam} – beam energy
(E^*_B, p^*_B) – B four momentum

Two almost uncorrelated variables

+ $\Delta E = E^*_B - E^*_{beam}$ signal at $\Delta E \approx 0$
+ $m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$ signal at $m_{ES} \approx m_B$

Energy substituted mass m_{ES}: E_{beam} replaces E_B

Resolutions

+ $\sigma^2_{\Delta E} = \sigma^2_{beam} + \sigma_E \approx \sigma_E \approx 10 - 40$ MeV
+ $\sigma^2_{m_{ES}} = \sigma^2_{beam} + \frac{p^2}{m^2_B}\sigma^2_p \approx \sigma^2_{beam} \approx 2.6$ MeV

Main B Reconstruction Variables – $\Upsilon(4S)$

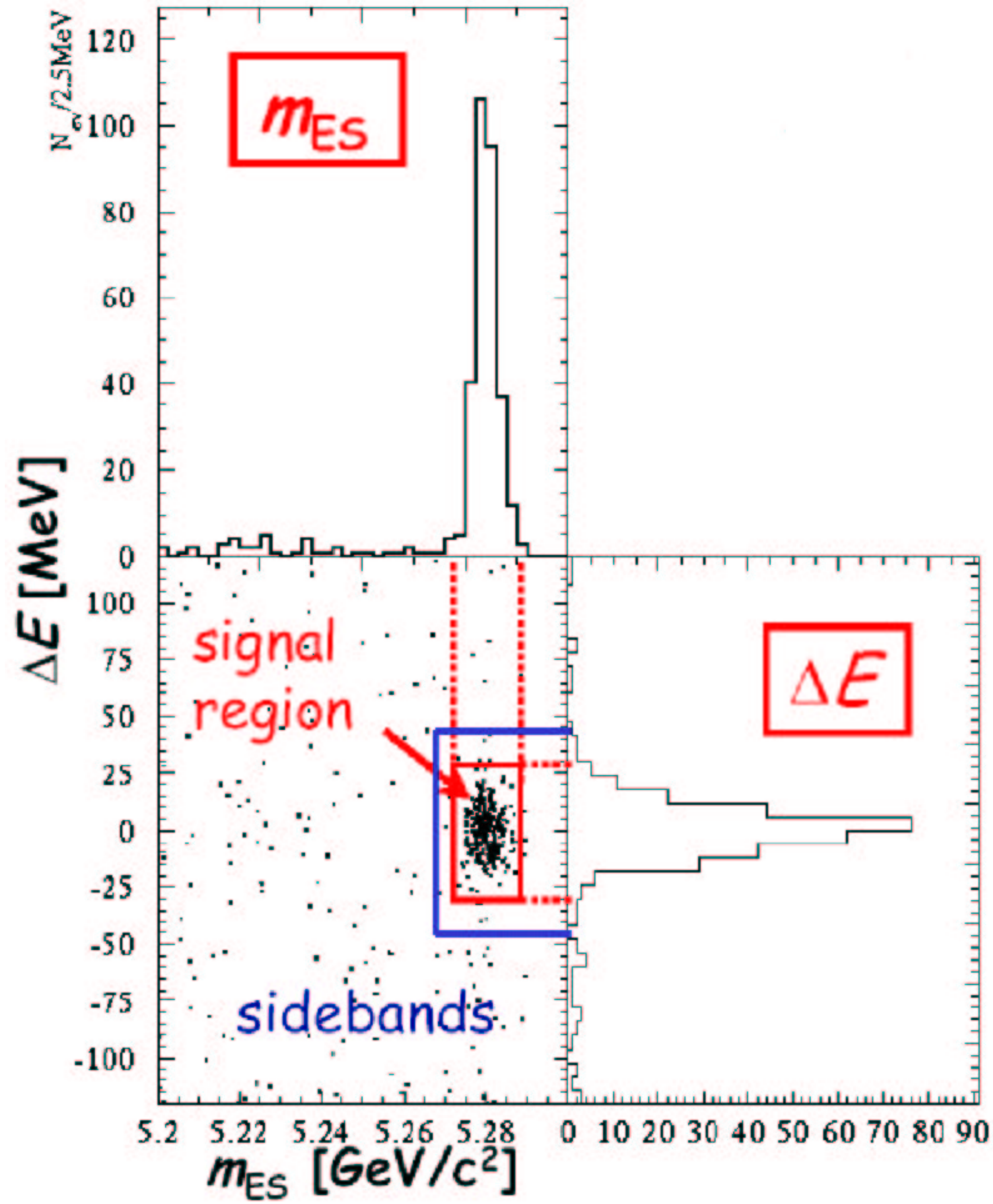
Channel: $B^0 \to J/\psi K_S^0$

Signal region

+ $\pm 3\sigma$ in m_{ES} and ΔE

Sideband region

+ rest window for bg

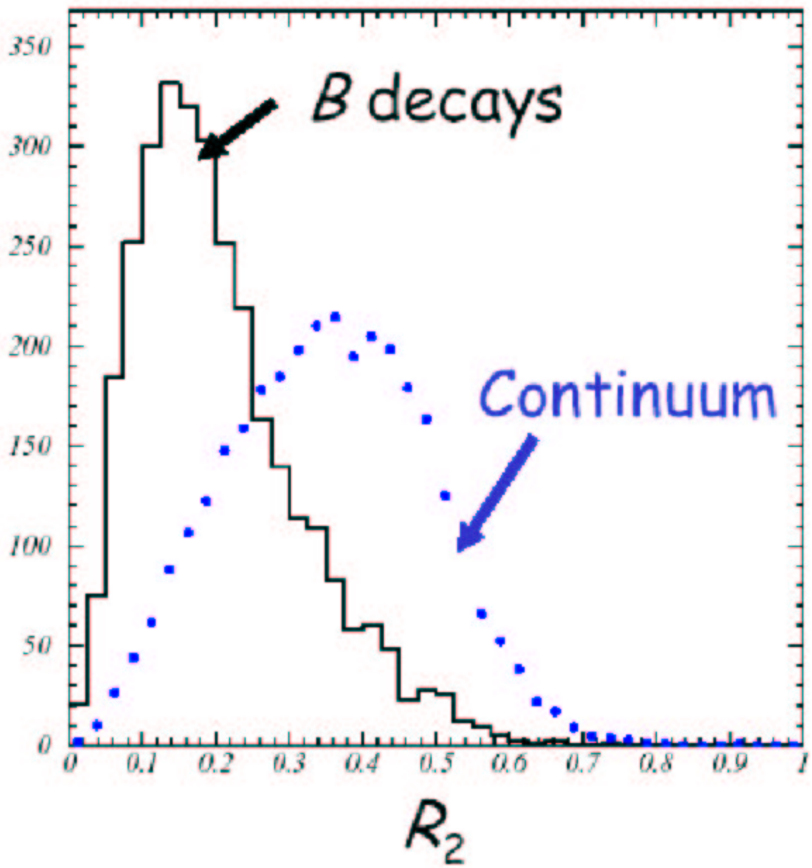


Continuum Background Supression – $\Upsilon(4S)$

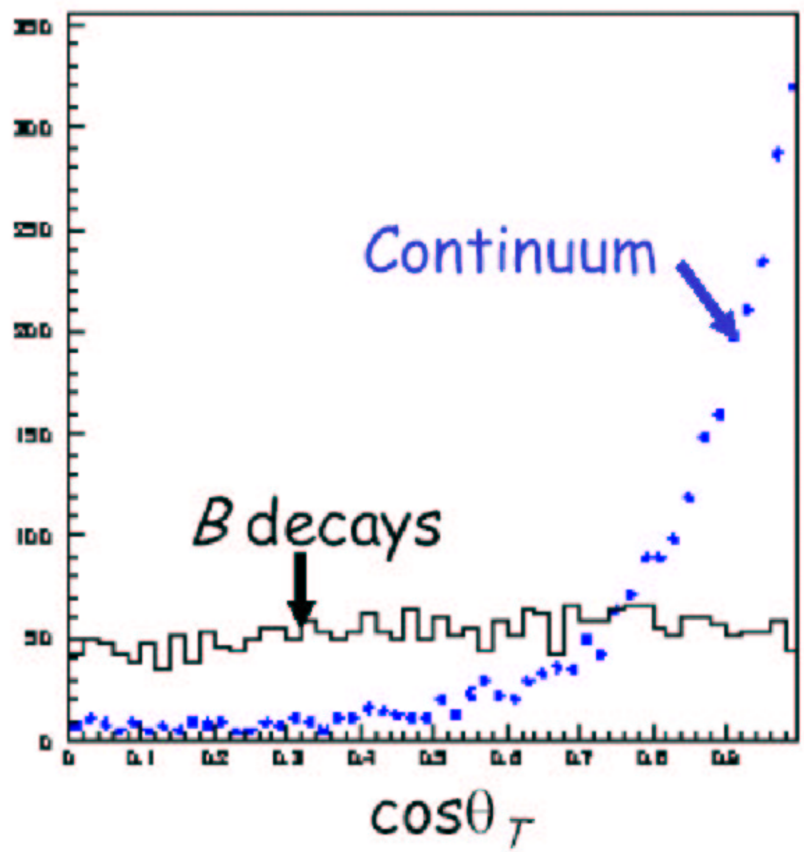
Main Idea: $B\bar{B}$ is spherical in $\Upsilon(4S)$ CM since produced at rest

Continuum background is jet-like

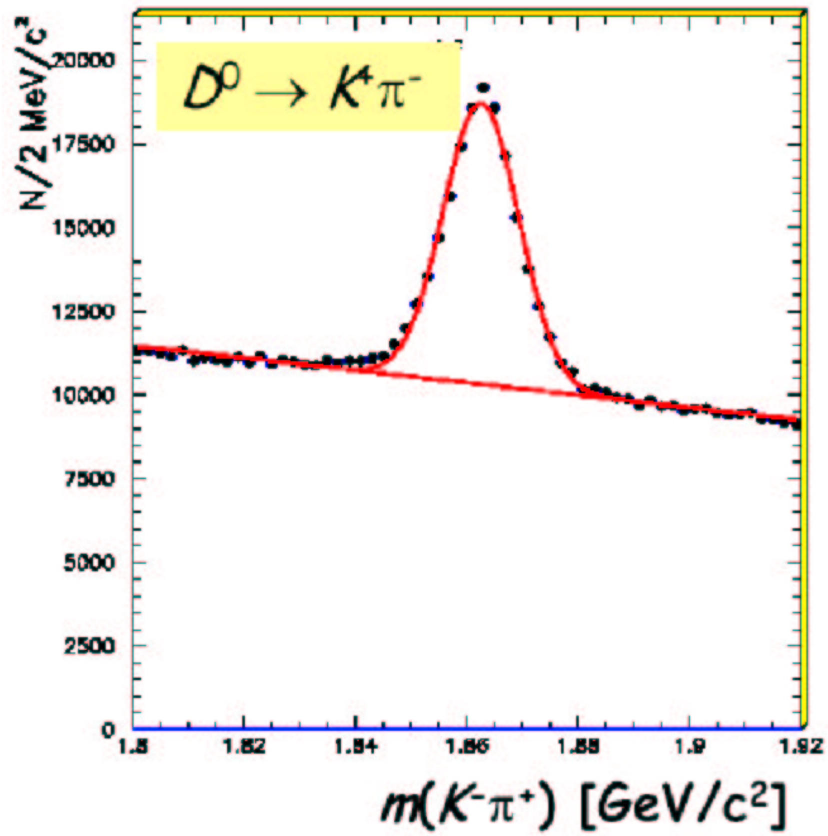
Ratio of $2^{nd}/0^{th}$ Fox-Wolfram moments

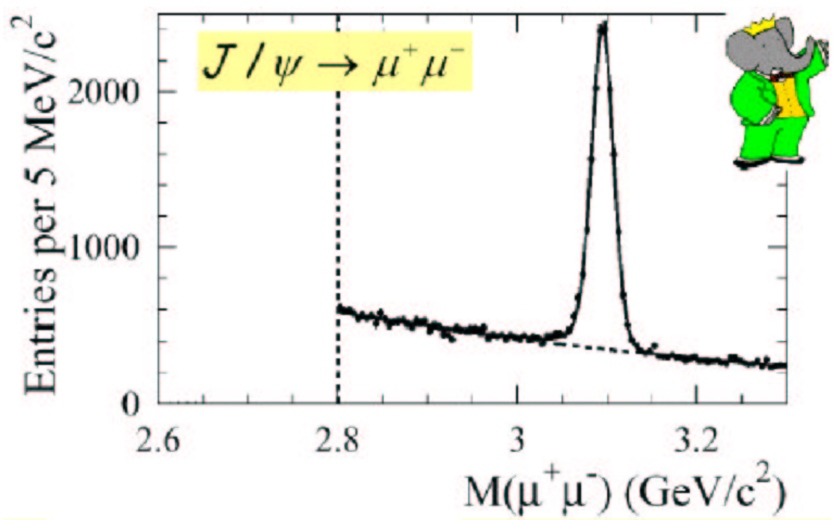


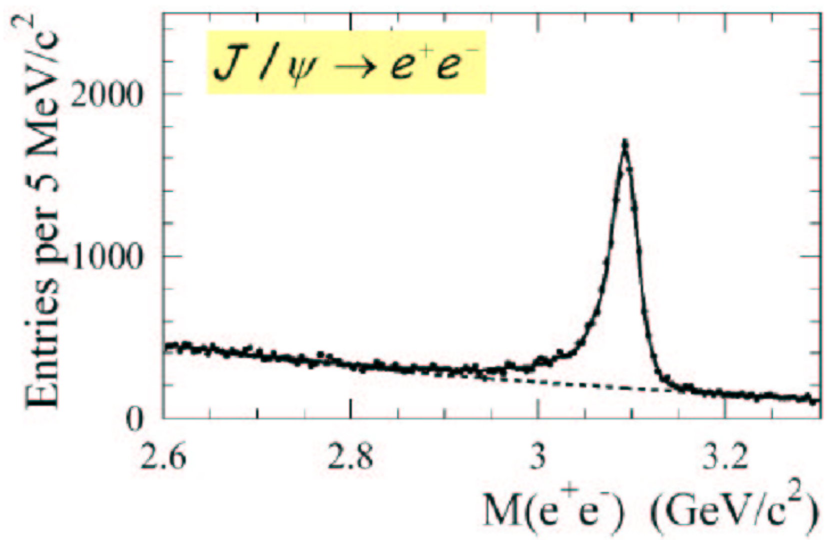
Angle of thrust axis of *rest* wrt B candidate direction θ_T



Subresonances – $\Upsilon(4S)$

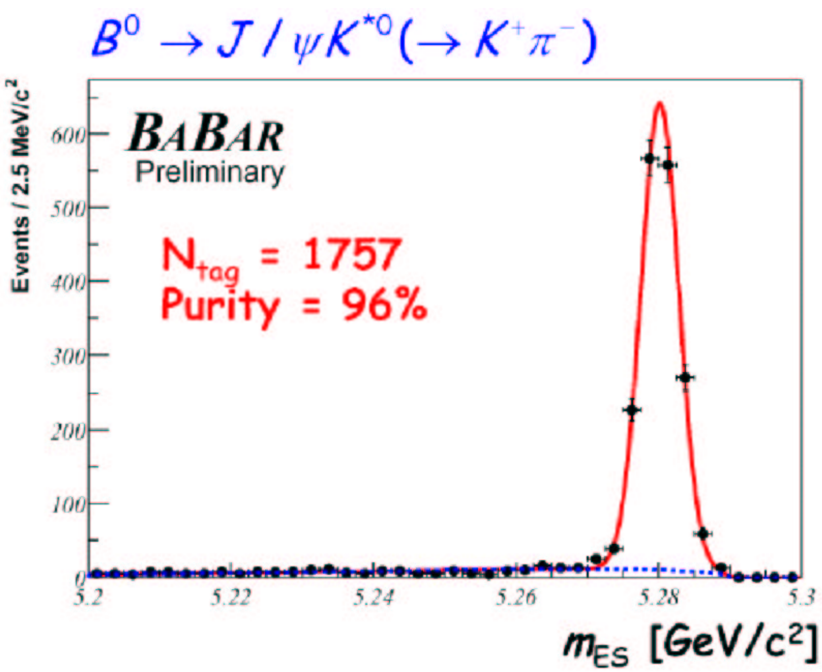


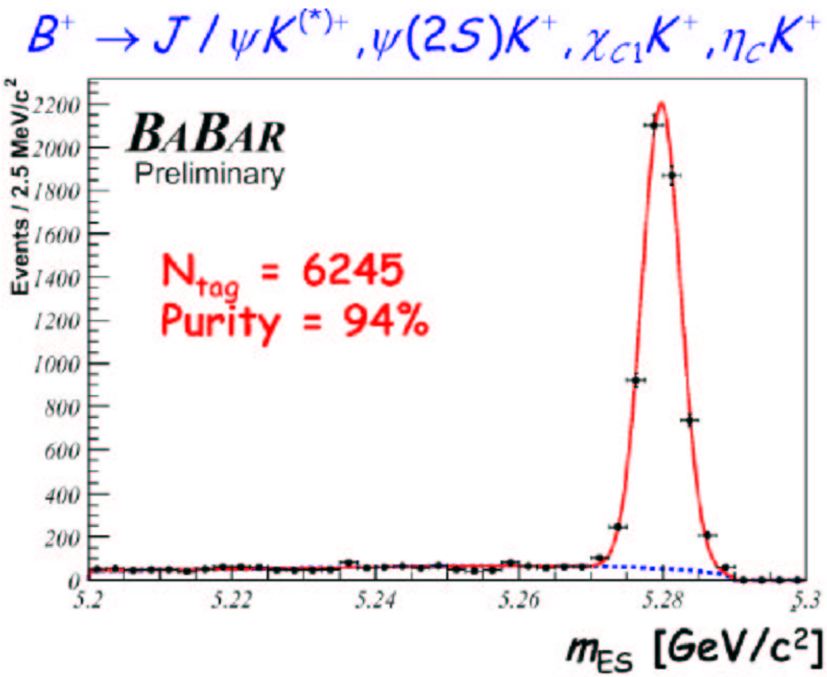




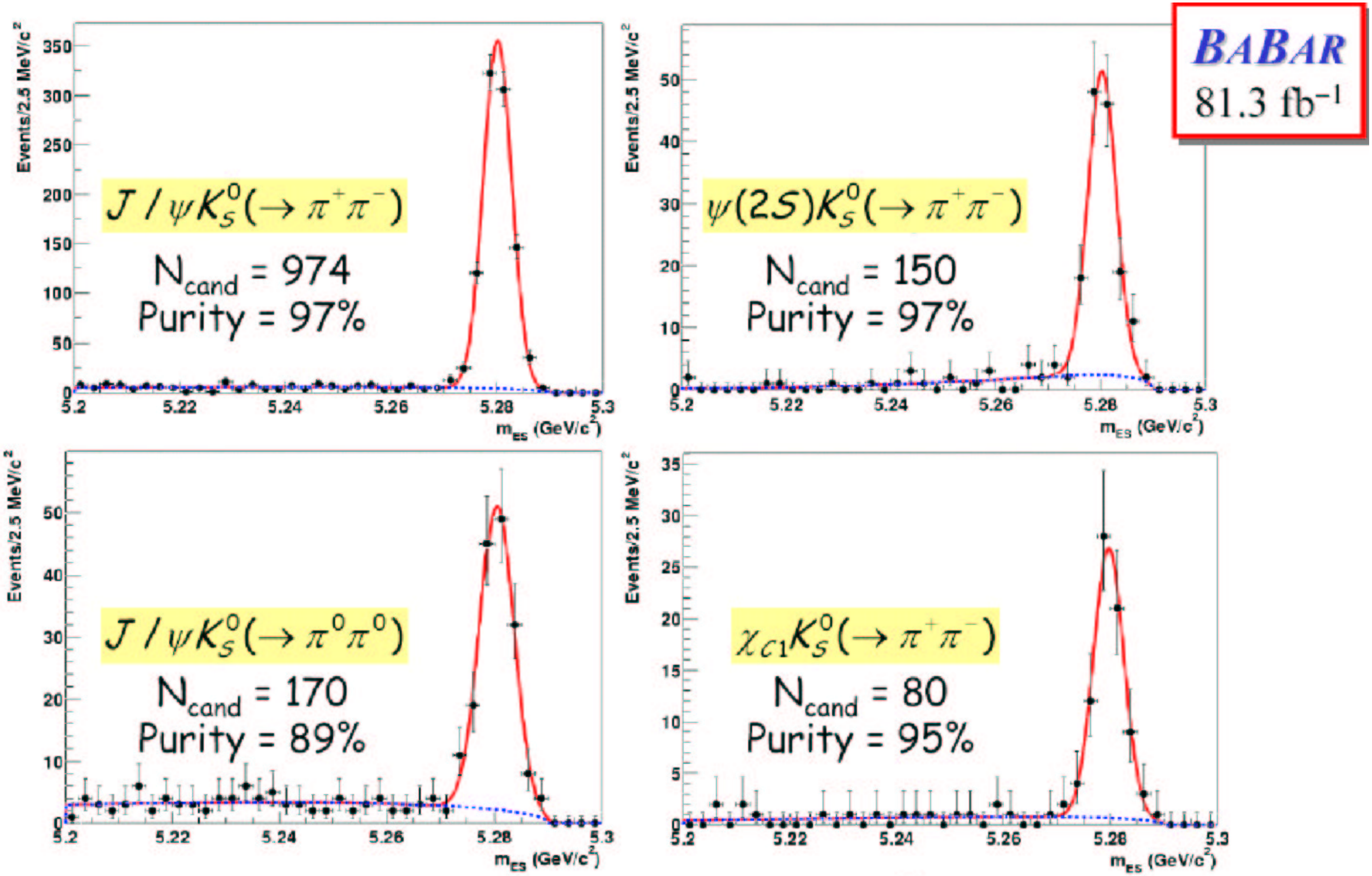
masses are constraint after selection

Hadronic Samples at $\Upsilon(4S)$ – Self-Tagging





Hadronic Samples at $\Upsilon(4S)$ – *CP* Eigenstate



Candidates & purity for m_{ES} > 5.27 GeV/c^2

Reconstruction of *b* Hadrons at Tevatron

No knowledge of total energy of collision

Basically no constraints on energy or momentum

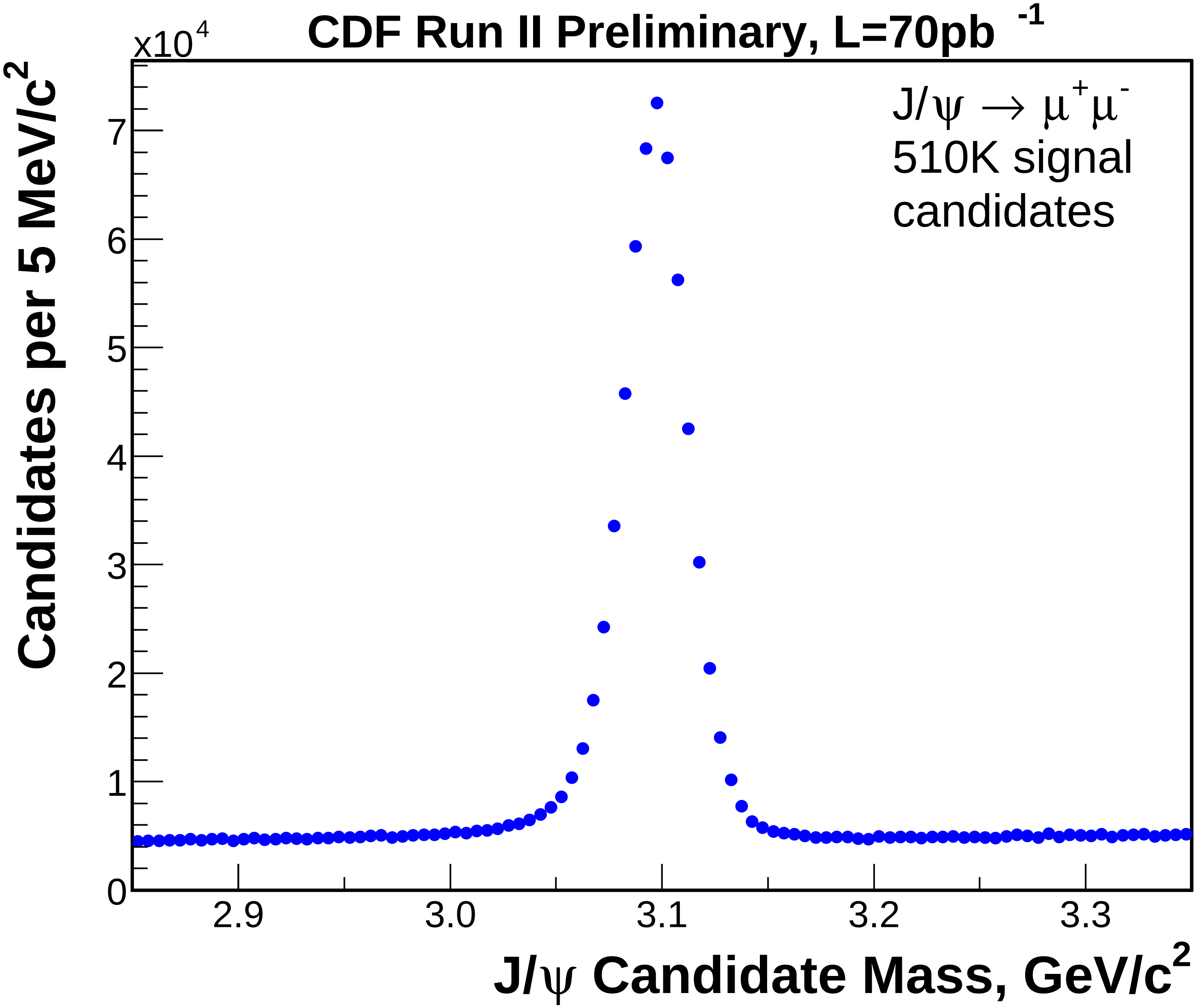
Use high p_T leptons

Use high p_T resonances

Use precise knowledge of vertex positions

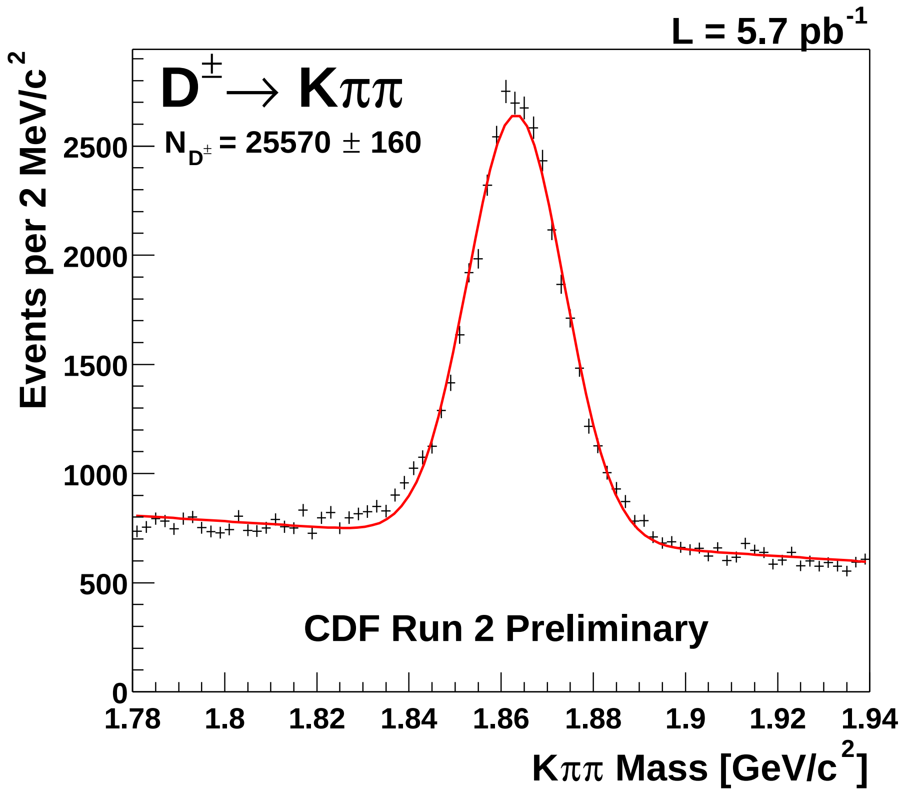
+ require *b* hadron to point at primary vertex
+ require $L_{xy} > 0$ typically 100 μm (careful: bias ct)

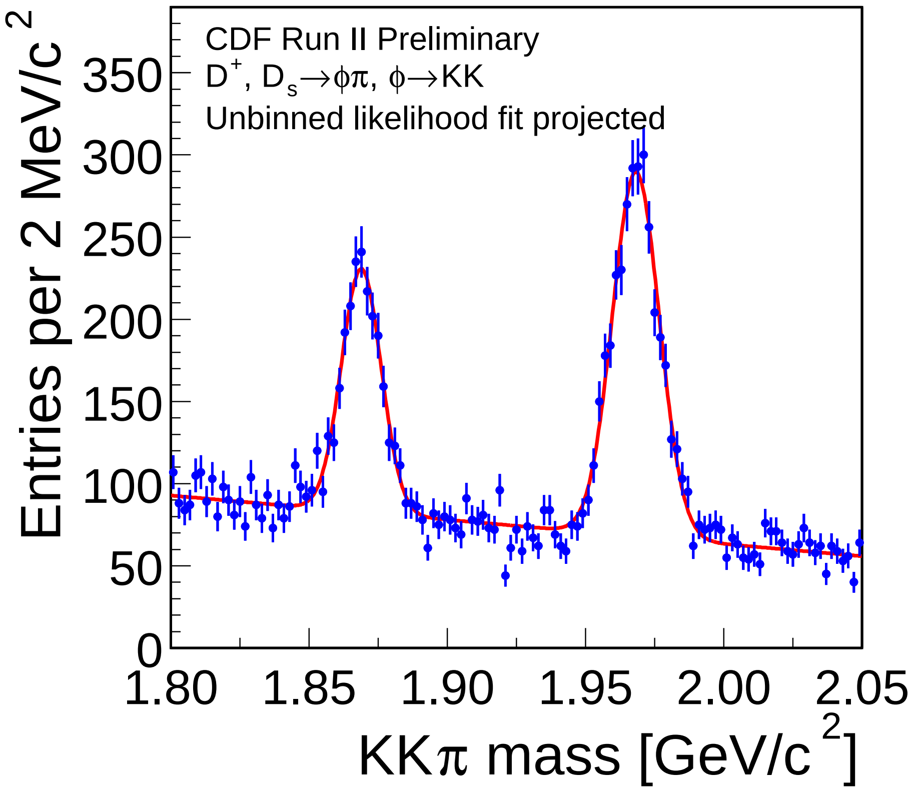
Subresonances at CDF – J/ψ



Subresonances at CDF – Charm

Result of diplaced track trigger!!
No Lepton was harmed in making these plots

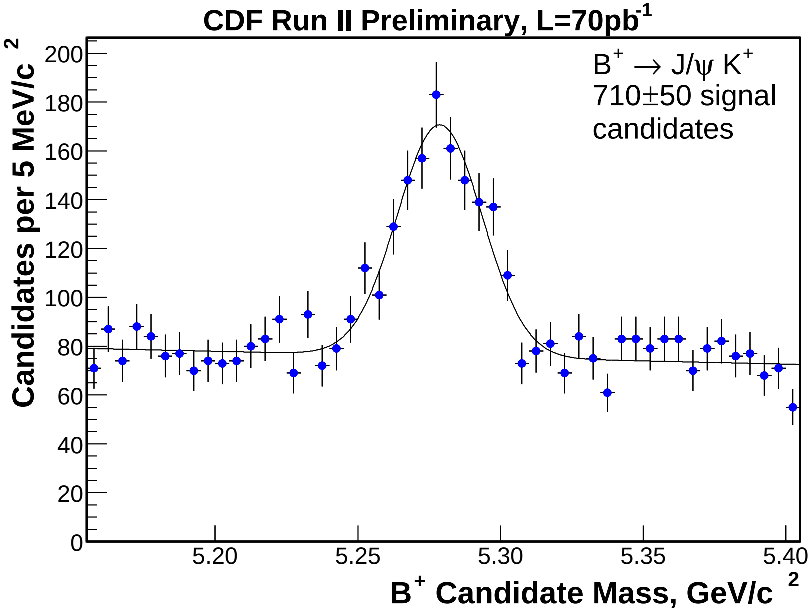


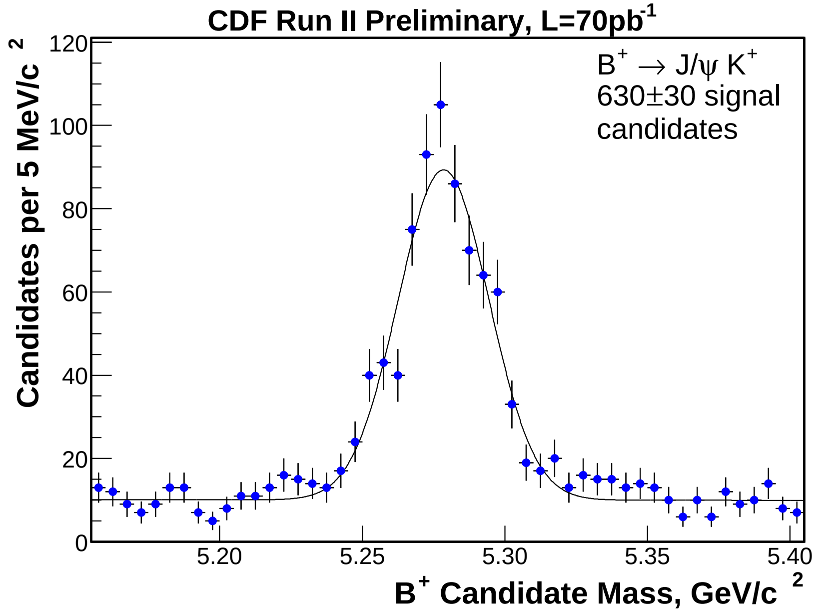


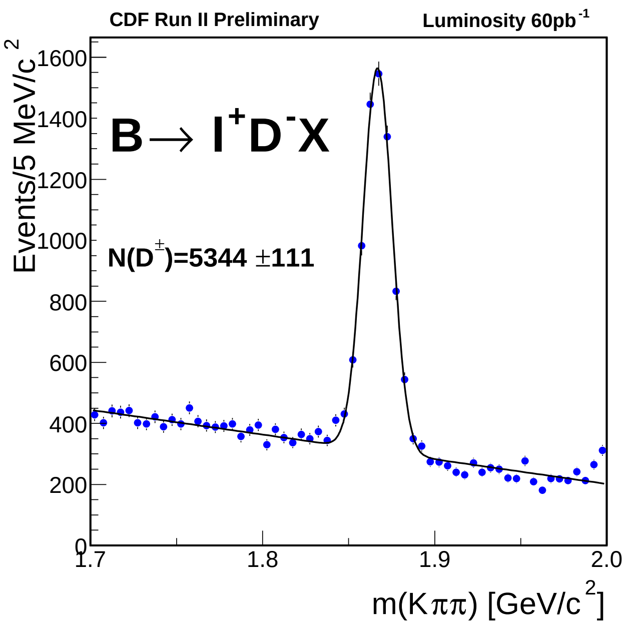
20 times more data available

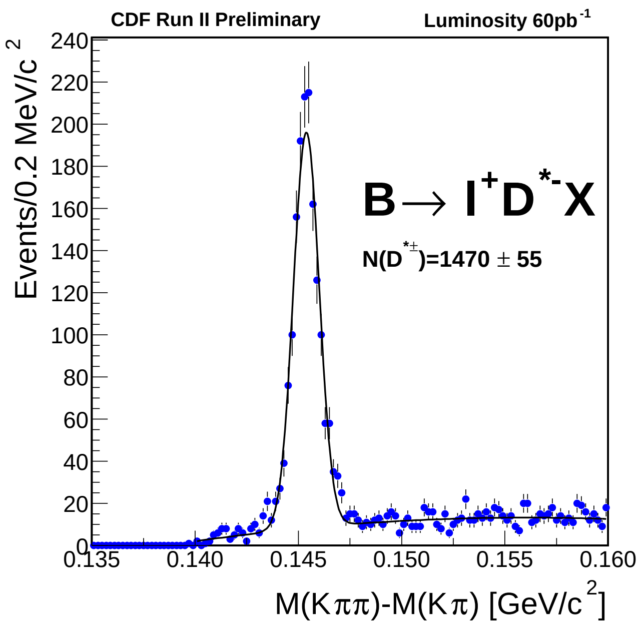
used to measure mass difference

Self Tagging Final States at CDF





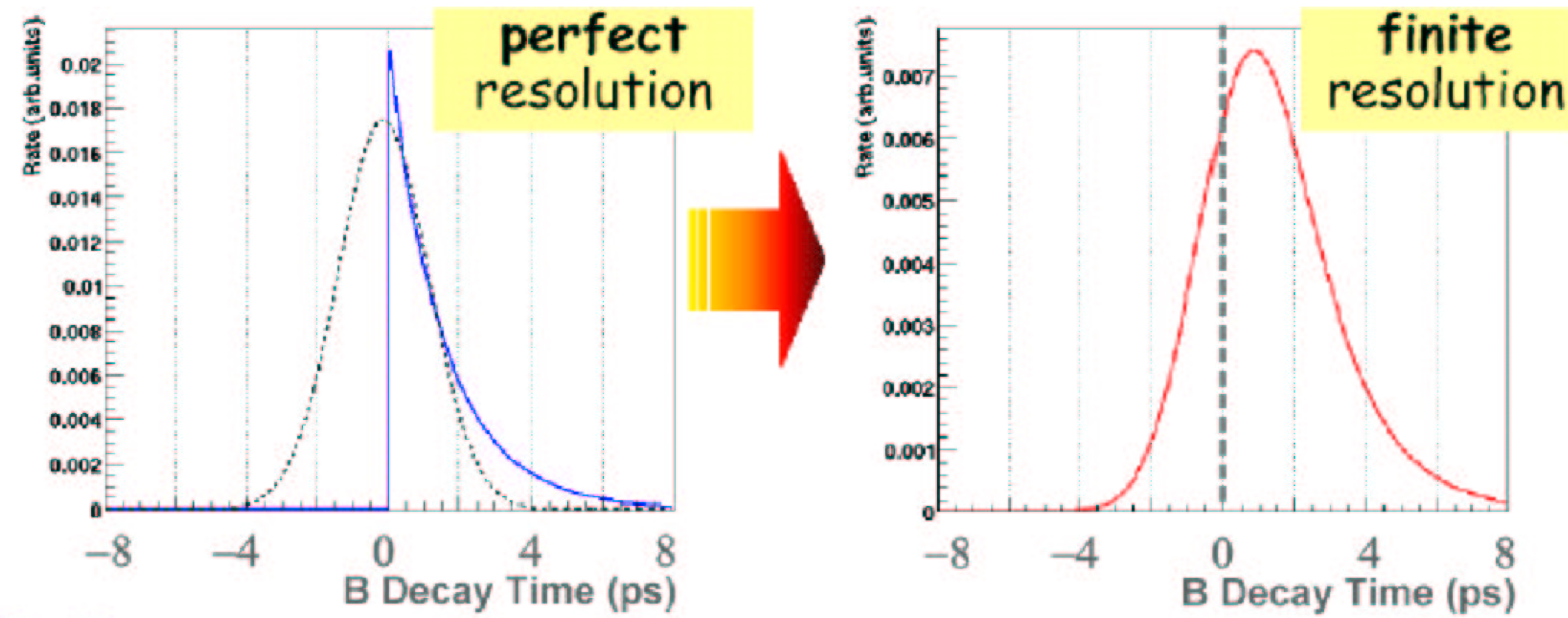




Measurement of t or Δt

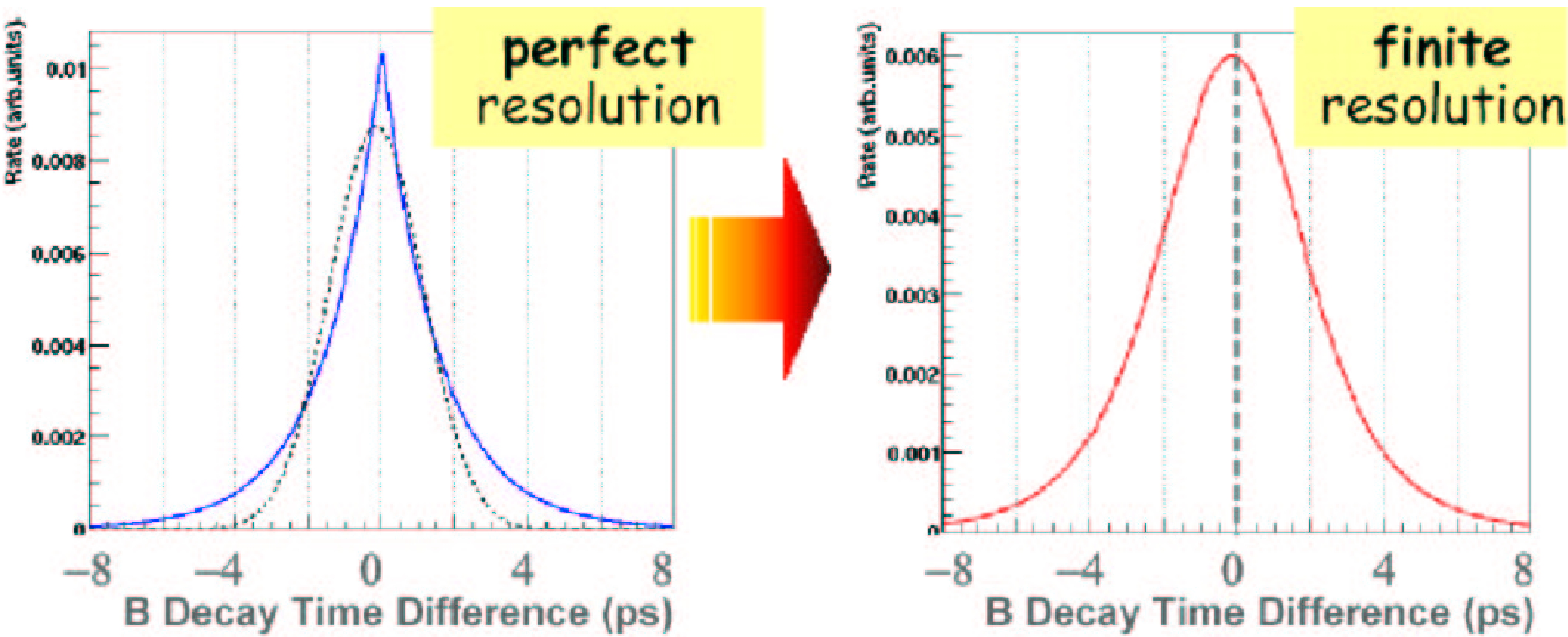
Measurement of *t* at Tevatron/LEP

Primary vertex is well known point
Negative tails allow to control resolution function



Measurement of Δt at B Factories

Determine Δt from Δz between B Mesons
Resolution function and lifetime are convoluted



B Lifetime Measurements at B Factories

BaBar (20.7 fb^{-1}) PRL 87 (2001) 201803

$\tau_{B^0} = 1.546 \pm 0.032 \pm 0.022$ ps
$\tau_{B^+} = 1.673 \pm 0.032 \pm 0.023$ ps
$\tau_{B^+}/\tau_{B^0} = 1.082 \pm 0.026 \pm 0.012$

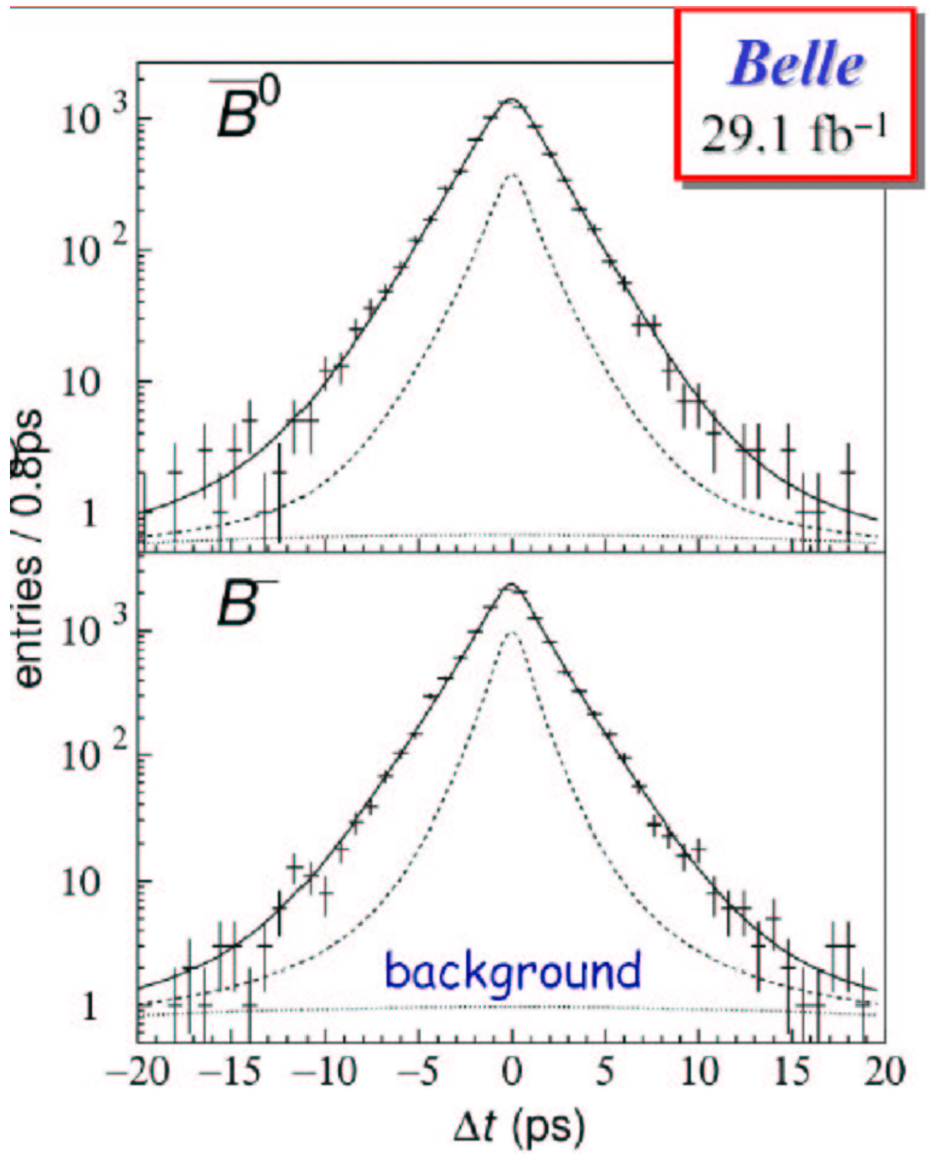
Belle (29.1 fb^{-1}) PRL 88 (2002) 171801

$\tau_{B^0} = 1.554 \pm 0.030 \pm 0.019$ ps
$\tau_{B^+} = 1.673 \pm 0.026 \pm 0.015$ ps
$\tau_{B^+}/\tau_{B^0} = 1.091 \pm 0.023 \pm 0.014$

Agree within each other

Agree with world average

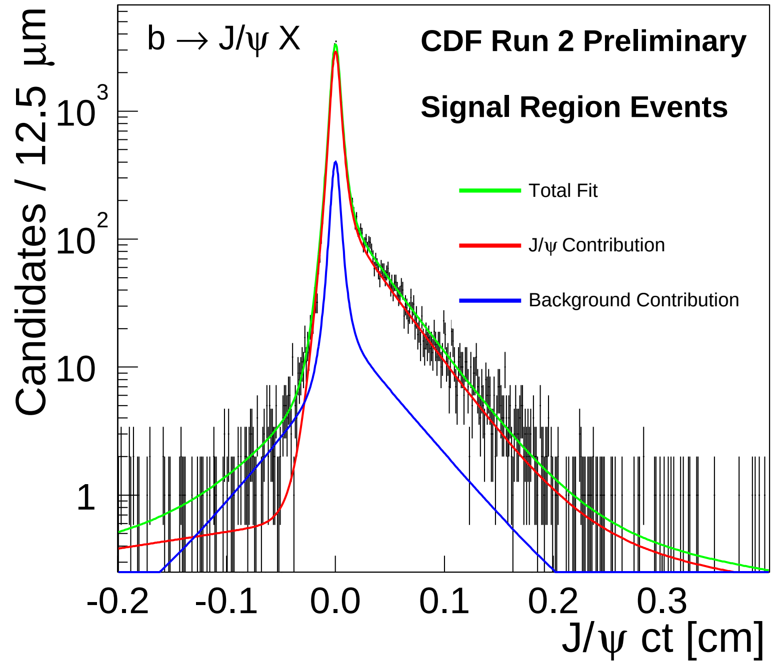
Proof of principle:
Control resolution function



B Lifetime Measurements at Tevatron

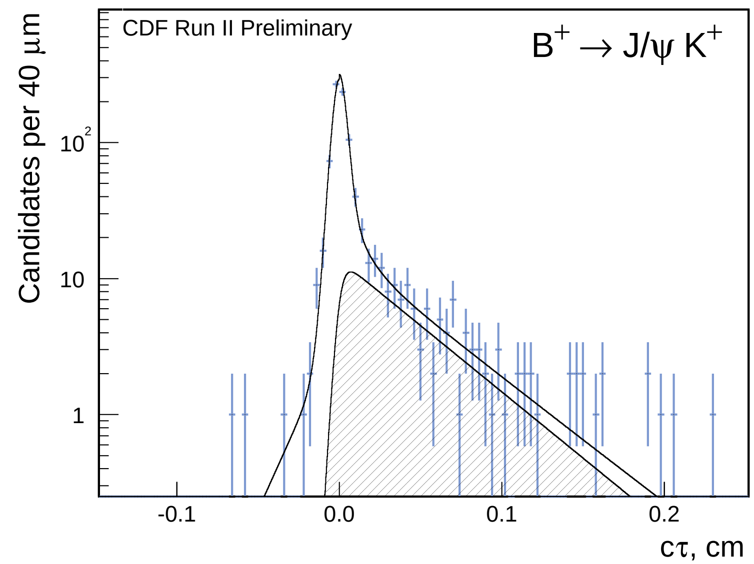
Large sample of $J/\psi \to \mu^+\mu^-$ events

- + calibrate resolution
- + understand alignment
- + measure inclusive B lifetime
- + so far only r-ϕ silicon used



Lifetime measurements

$$c\tau_{incl} = 458 \pm 10 \text{ (stat)} \pm 11 \text{ (sys)}\ \mu m$$
$$c\tau_{B^+} = 446 \pm 43 \text{ (stat)} \pm 13 \text{ (sys)}\ \mu m$$

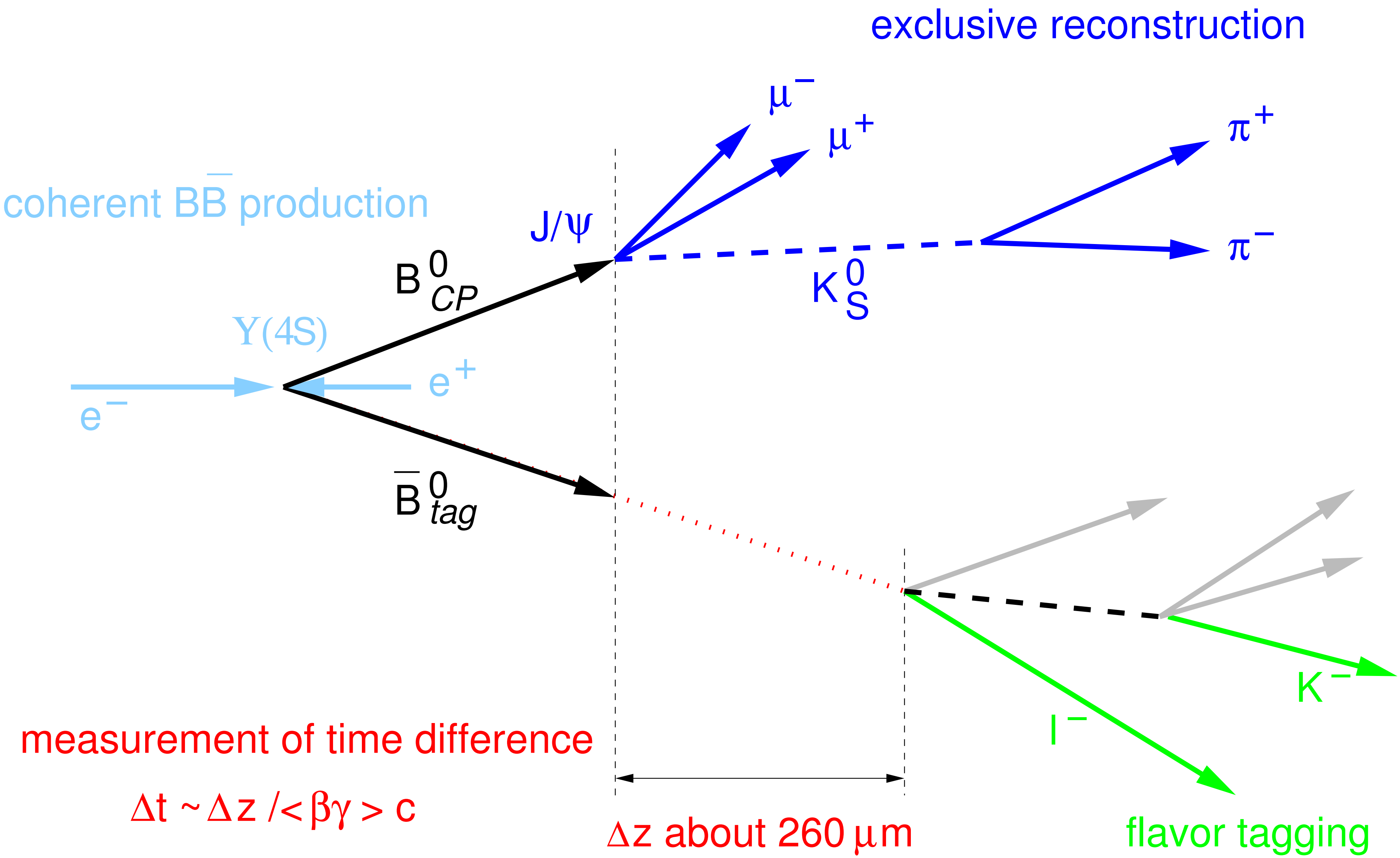


About CDF results

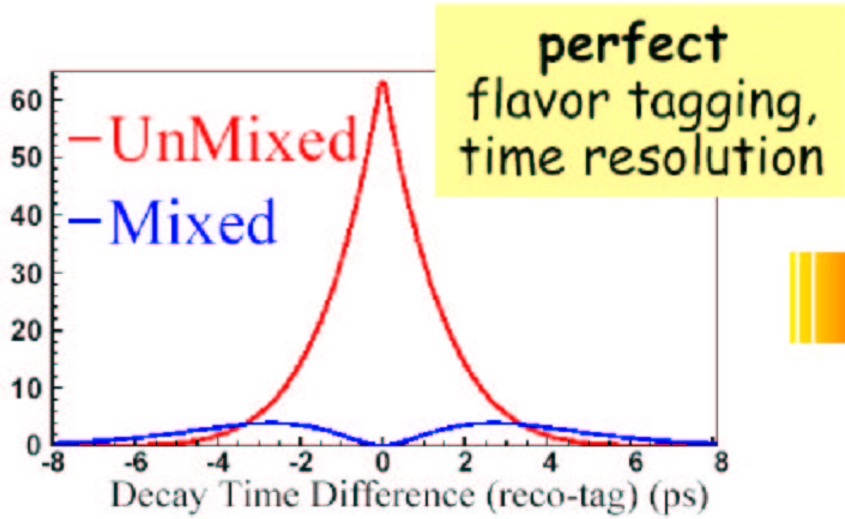
- + silicon already well understood
- + consistent with Run 1, world average
- + incl. systematics as Run 1
- + major improvements expected: Layer 00, 3D tracking, alignments
- + now ten times more data
- + very soon τ_{B_s} and τ_{Λ_b}

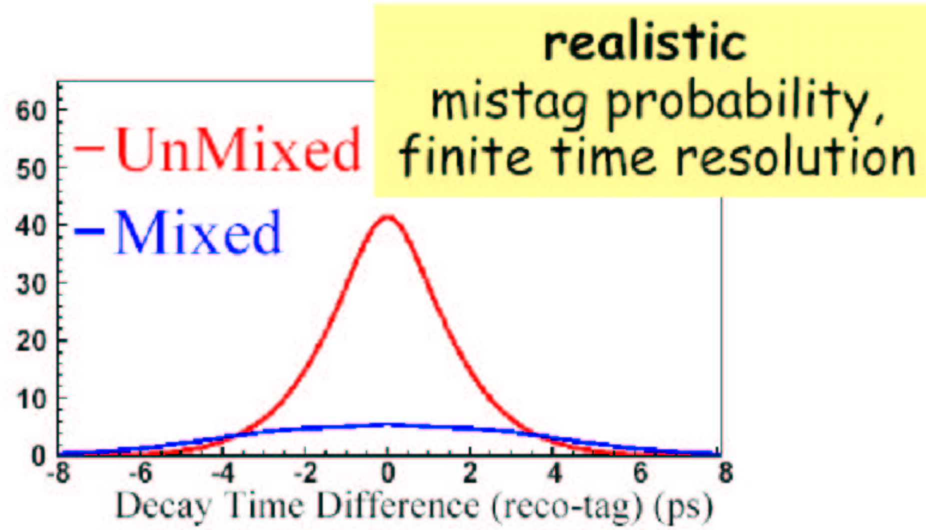
b Flavor Tagging

Detailed Cartoon of Measurement at $\Upsilon(4S)$



Distribution of Mixing at $\Upsilon(4S)$





Distribution of mixed and unmixed events

$$f_{mix,\pm}(\Delta t) = \left[\frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}(1 \pm (1-2w)\cos\Delta m_d \Delta t)\right] \otimes R(\Delta t)$$

$f_{mix,+}$ - means unmixed or different flavors

$f_{mix,-}$ - means mixed or same flavors

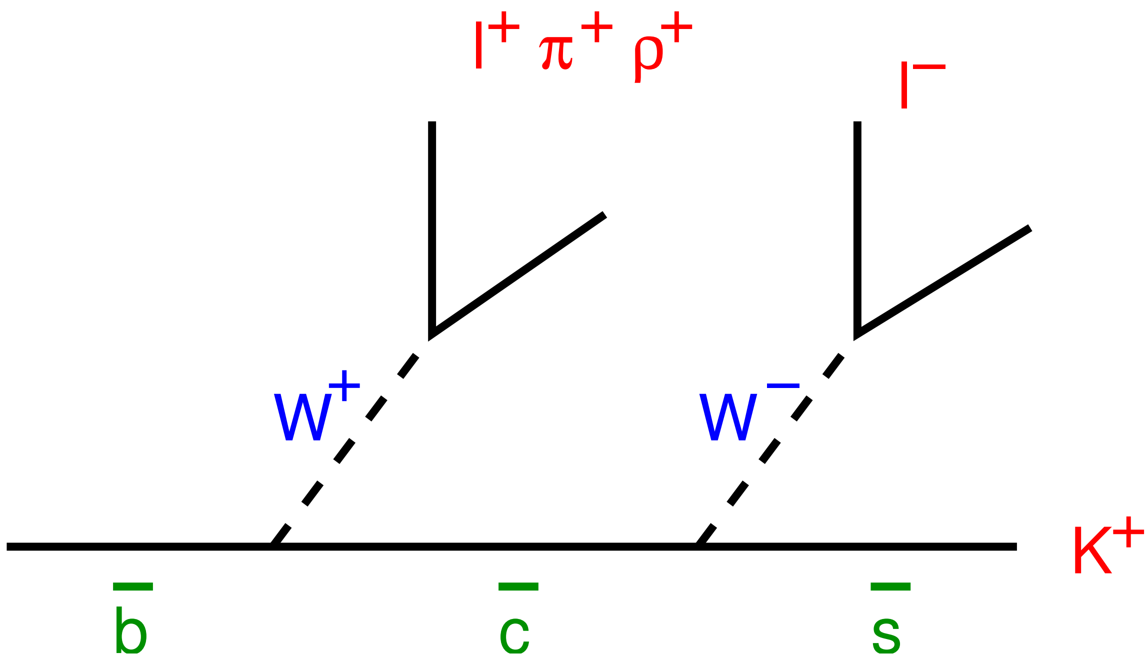
$1-2w$ - quality of the tagging algorithm (dilution)

$R(\Delta t)$ - detector resolution function

Methods of Flavor Tagging at *B* Factories

At *B* factories flavor tags rely on *tagging* side

- primary lepton $\quad B^0 \to D^{*-}\ell^+\nu$
- secondary lepton $\quad B^0 \to D^-\pi^+, D^- \to K^{*+}\ell^-\overline{\nu}$
- Kaon(s) $\quad B^0 \to \overline{D}X, \overline{D} \to K^+X$
- Soft pions from D^* decays $\quad B^0 \to D^{*-}X, D^{*-} \to \overline{D}^0\pi_s^-$
- Fast charged tracks



Flavor Tagging Performance at B Factories – BaBar

Tagging Algorithm	efficiency	wrong tag w	$Q = \varepsilon(1-2w)^2$
Lepton	10.9 ± 0.3	9.0 ± 1.4	7.4 ± 0.5
Kaon	35.8 ± 1.0	17.6 ± 1.0	15.0 ± 0.9
NeuralNet 1	7.7 ± 0.2	22.0 ± 2.1	2.5 ± 0.4
NeuralNet 2	13.8 ± 0.3	35.1 ± 1.9	1.2 ± 0.3
Combined	$68.4 \pm 0.7\%$	$9.0 \pm 1.4\%$	$26.1 \pm 1.2\%$

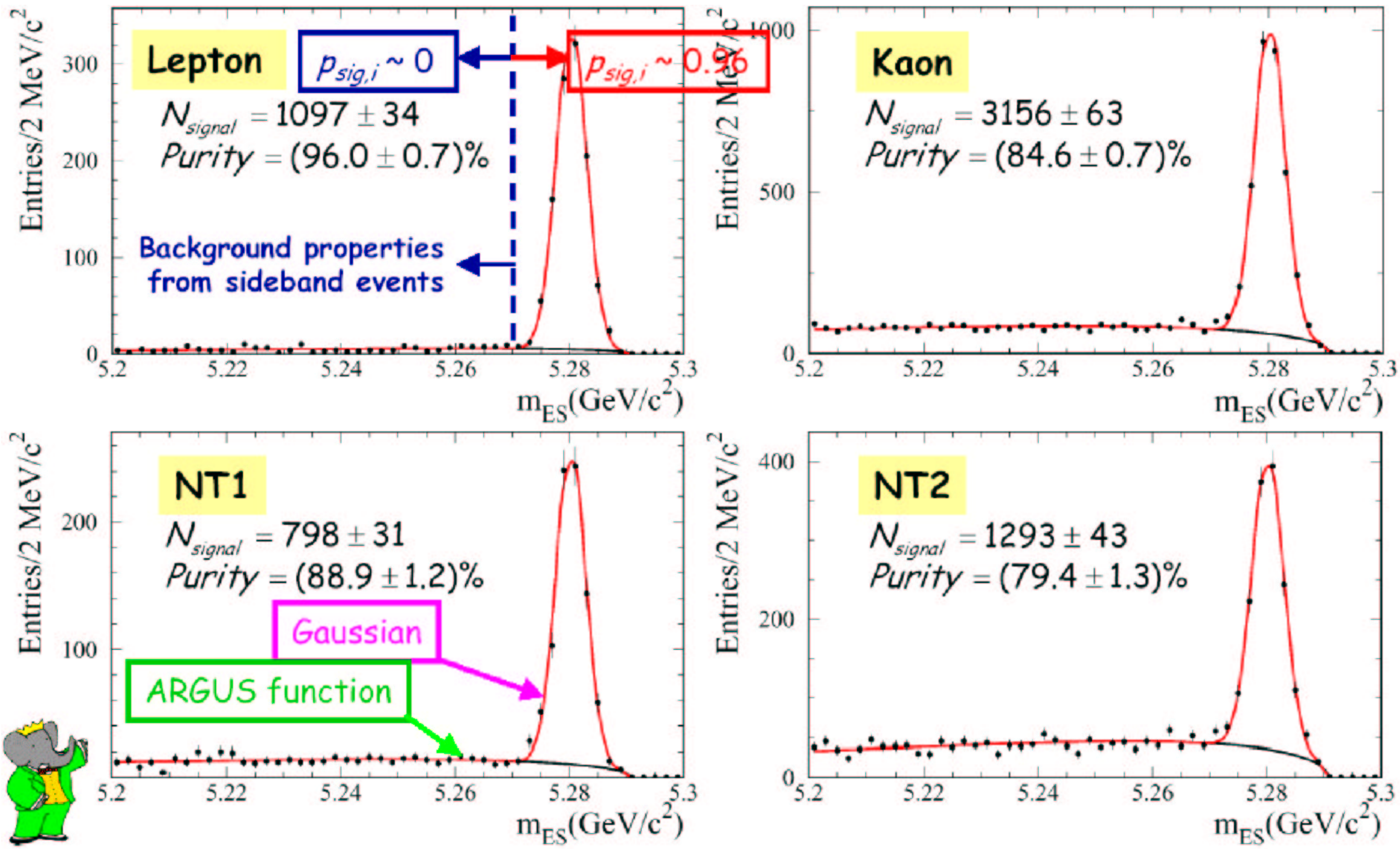
Large sample of fully reconstructed events allows precise measurement

Calibrate the taggers using data

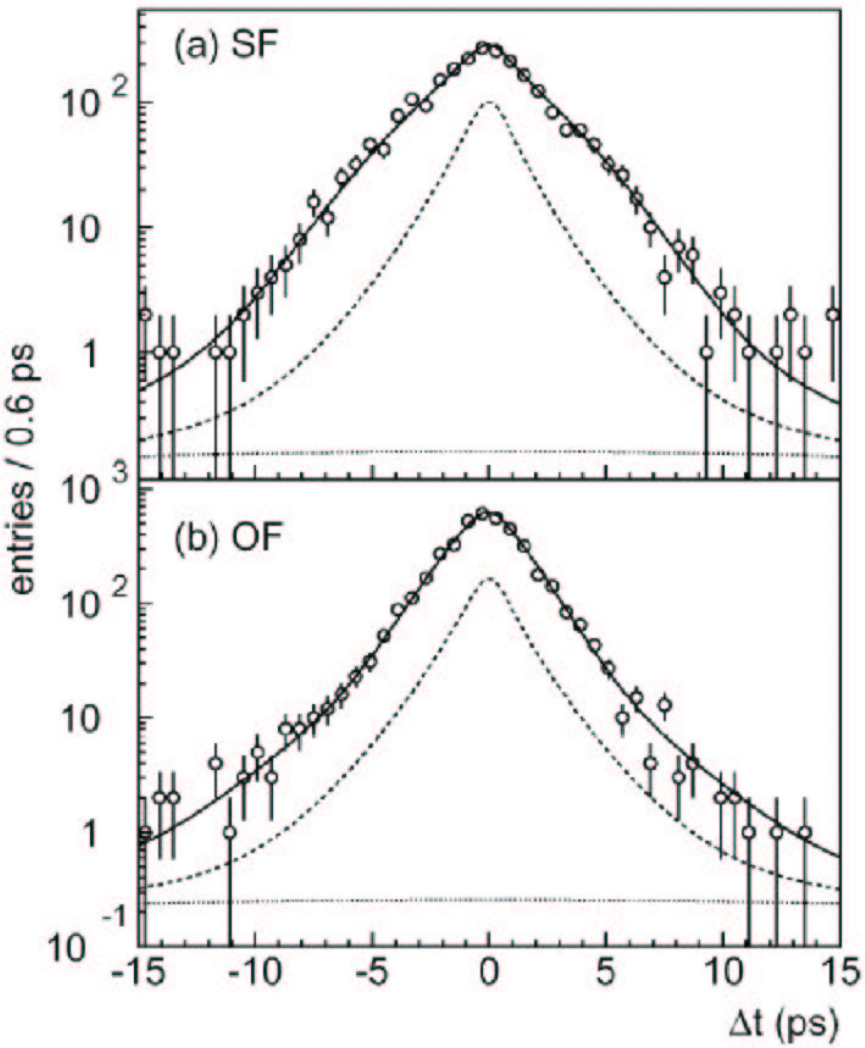
No MonteCarlo used here

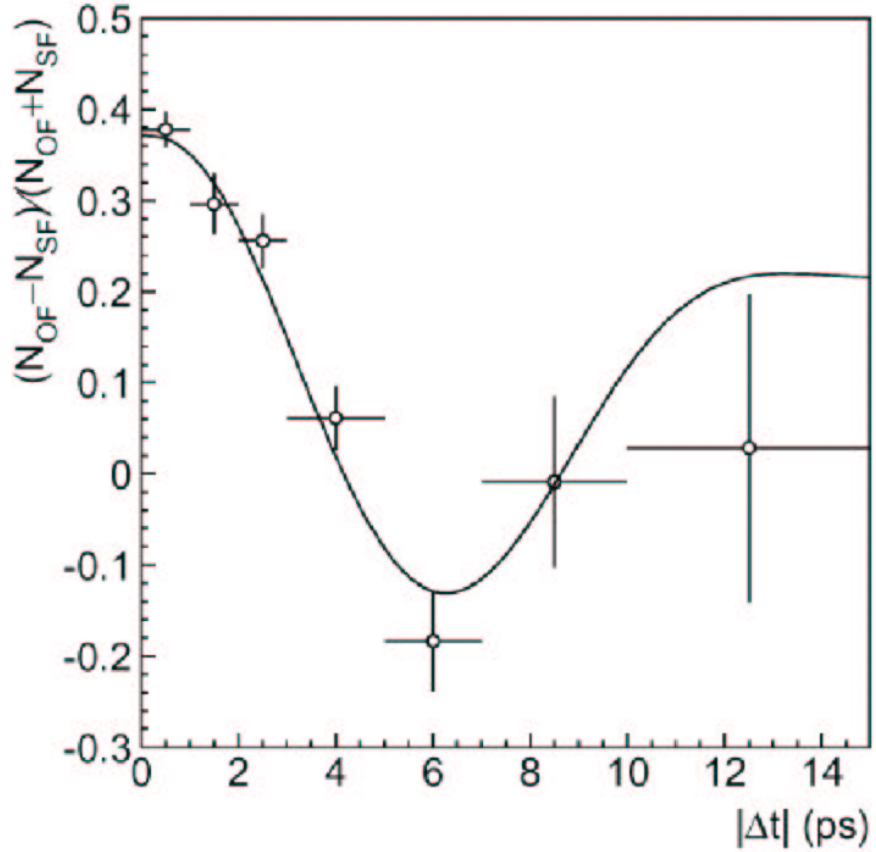
Quality meter: $\sigma(\sin 2\beta)_{stat} \propto 1/\sqrt{Q}$

Event Samples for Mixing Measurement – BaBar



Mixing Measurements – BaBar/Belle



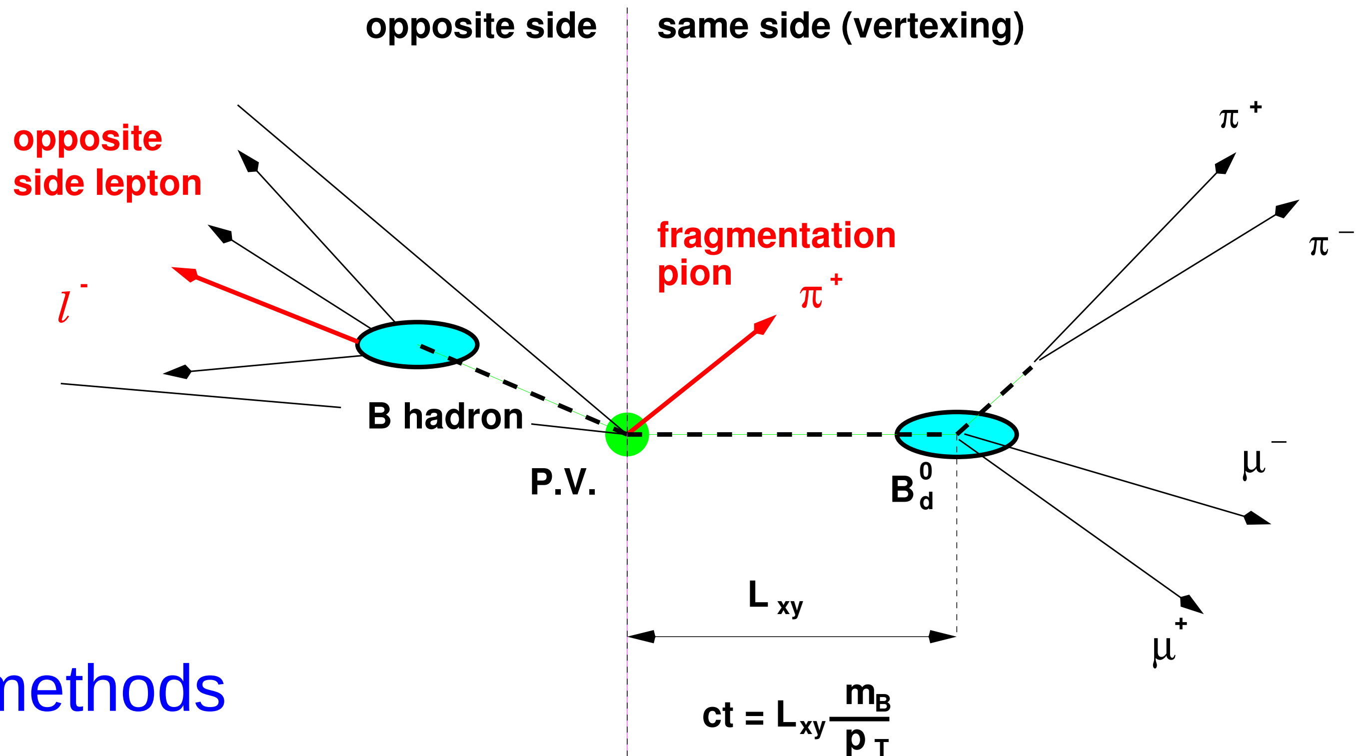


BELLE
29.1 fb^{-1}

$\Delta m_d = 0.528 \pm 0.017 \pm 0.011\ \text{ps}^{-1}$ (Belle)
$\Delta m_d = 0.516 \pm 0.016 \pm 0.010\ \text{ps}^{-1}$ (Babar)

PRL 88 (2002) 221802

Flavor Tagging at the Tevatron



Tagging methods

- lepton opposite side tag
- kaon OS tag
- jet charge OS tag
- pion same side tag
- kaon same side tag (B_s)

Same side tagging

Flavor Tagging at the Tevatron

Example: taggers for $B^0 \to J/\psi K_S^0$

Method	ε	$D = 1 - 2w$	εD^2
Lepton	$(5.6 \pm 1.8)\%$	$(62.5 \pm 14.6)\%$	$(2.2 \pm 1.2)\%$
Jet Charge	$(40.2 \pm 3.9)\%$	$(23.5 \pm 6.9)\%$	$(2.2 \pm 1.3)\%$
Same Side	$(\approx 70)\%$	$(\approx 17)\%$	$(2.1 \pm 0.5)\%$
Total			$(6.3 \pm 1.7)\%$

Tagger depend on kinematics of event sample: trigger bias

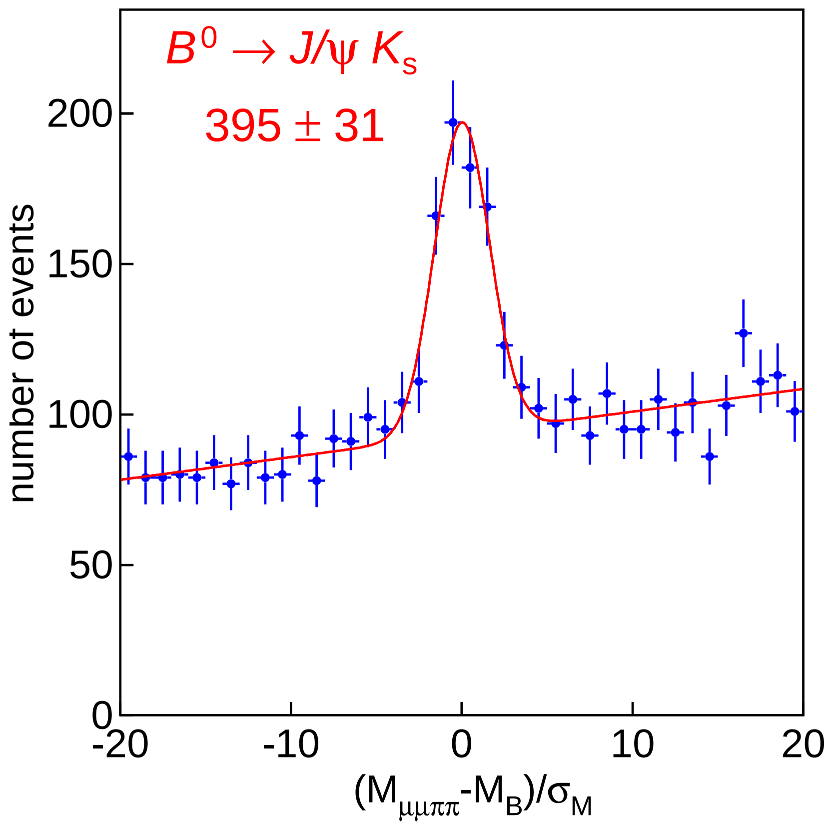
Measure *CP* asymmetry, $\sin 2\beta$

$$A_0(t) \equiv \frac{N(t)_{\mathrm{B}^0 \to f_{CP}} - N(t)_{\overline{\mathrm{B}^0} \to f_{CP}}}{N(t)_{\mathrm{B}^0 \to f_{CP}} + N(t)_{\overline{\mathrm{B}^0} \to f_{CP}}} = D \sin 2\beta \, \sin(\Delta m_q \, t)$$

For $\sin 2\beta$: measure Dilution $(1 - 2w)$ first $\to$ calibration sample

CDF used: $B^0 \to J/\psi K^{*0}$ extrapolate different kinematics

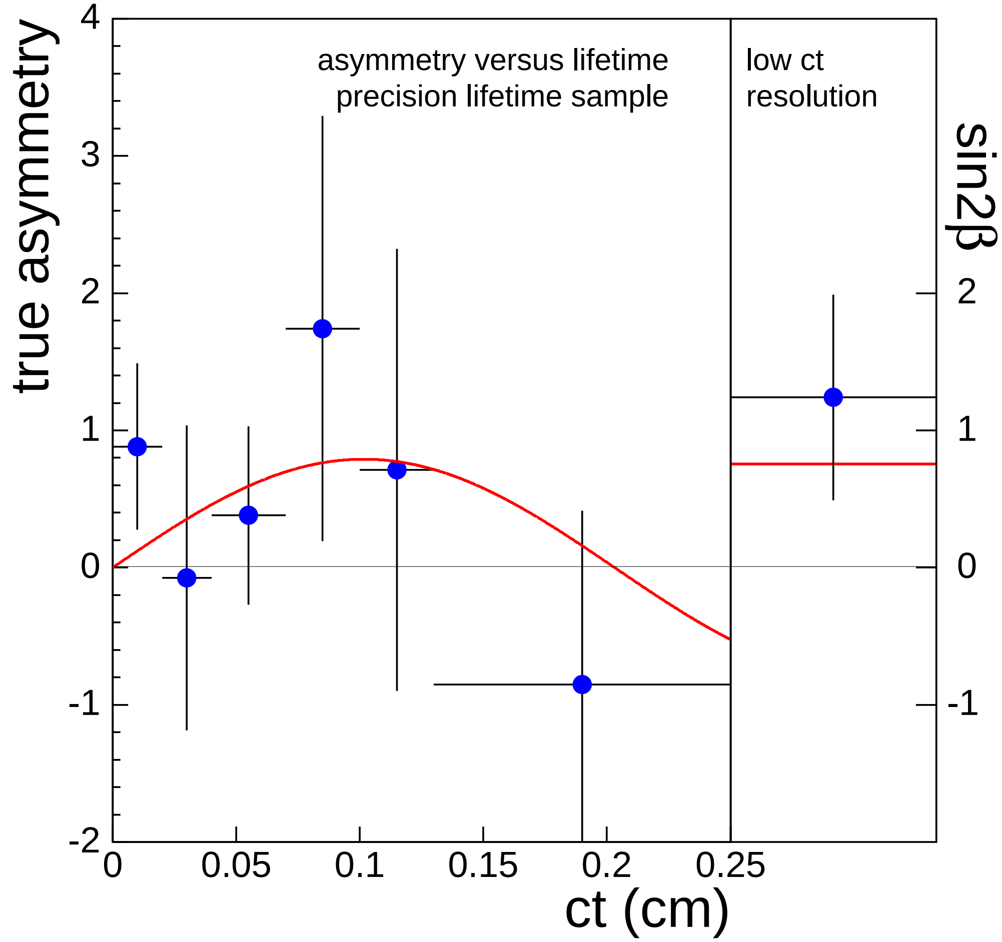
First $\sin 2\beta$ at CDF (1999)



Same side π, jet charge and soft lepton

$\sin 2\beta = 0.79\,^{+0.41}_{-0.44}$ $\quad \varepsilon D^2 = 6.3 \pm 1.7\%$

first presented 1999: PRD 61 (2000) 072005

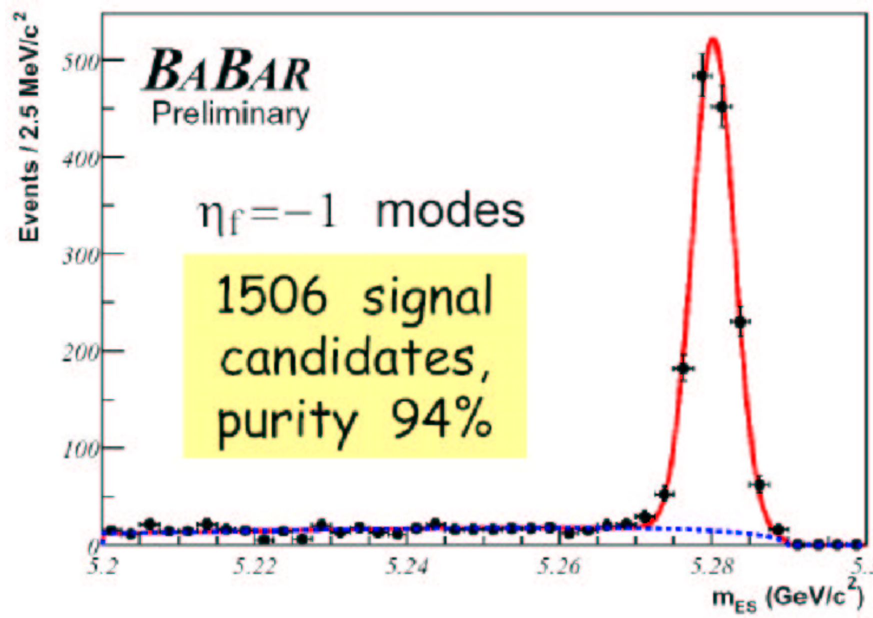


Not very clean but ≈ 400 events
No significant *CP* violation yet

The real $\sin 2\beta$ from the B Factories

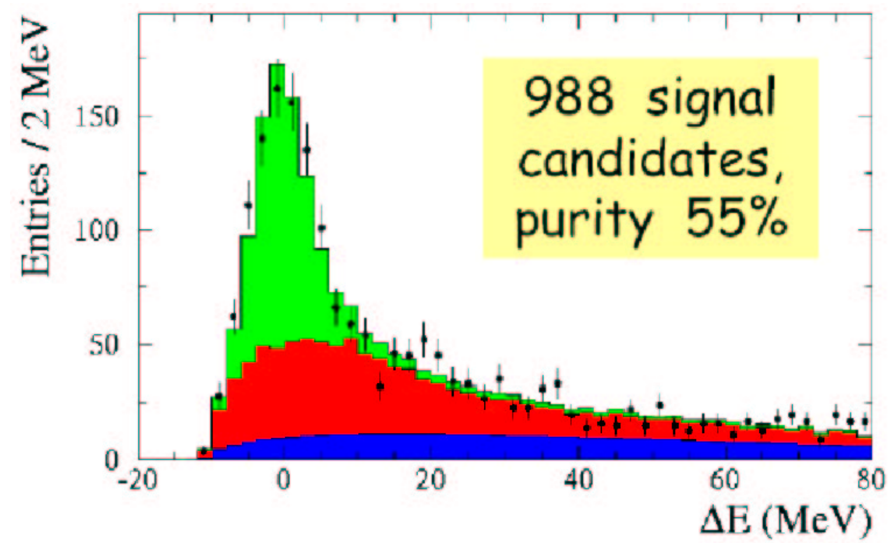
CP samples $\eta_f = -1$

- $B^0 \to J/\psi K^0_S(\to \pi^+\pi^-)$
- $B^0 \to J/\psi K^0_S(\to \pi^0\pi^0)$
- $B^0 \to \psi(2S)(\to \ell^+\ell^-)K^0_S$
- $B^0 \to \psi(2S)(\to J/\psi\pi^+\pi^-)K^0_S$
- $B^0 \to \chi_{c1}(\to J/\psi\gamma)K^0_S$
- $B^0 \to \eta_c(\to KK\pi)K^0_S$



CP samples $\eta_f = +1$

- $B^0 \to J/\psi K^0_L$



Integrated luminosity

Babar: 81.3 fb^{-1}

Improved tagging:

$\varepsilon D^2 = 28.1 \pm 0.7\%$

Asymmetries – Mixing and *CP*

Mixing asymmetry, Δm_d

$$A_{mix}(t) \equiv \frac{N(t)_{unmix} - N(t)_{mix}}{N(t)_{unmix} + N(t)_{mix}} = D\ \cos(\Delta m_d\, t)$$

CP asymmetry, $\sin 2\beta$

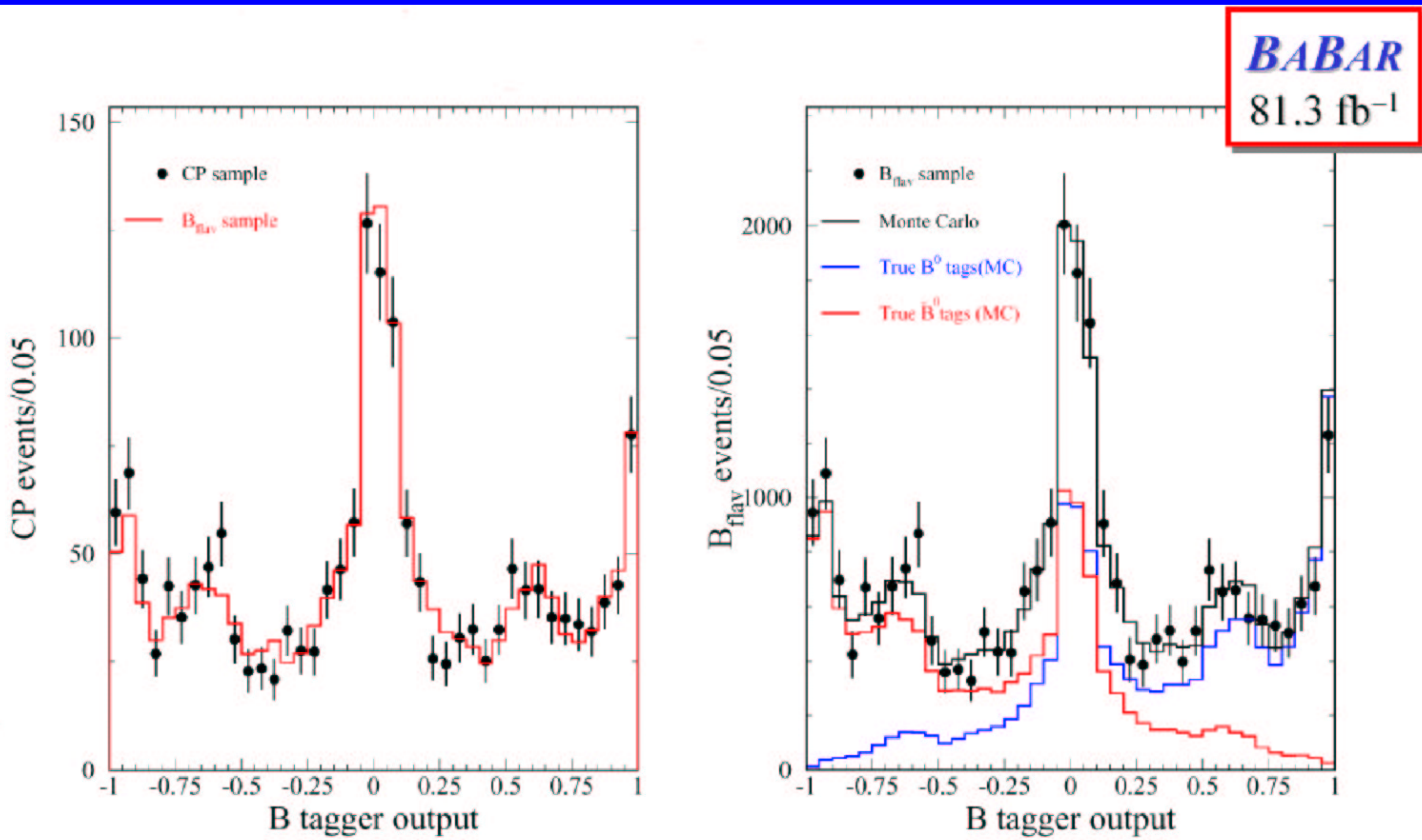
$$A_{CP}(t) \equiv \frac{N(t)_{\mathrm{B}^0 \to f_{CP}} - N(t)_{\overline{\mathrm{B}^0} \to f_{CP}}}{N(t)_{\mathrm{B}^0 \to f_{CP}} + N(t)_{\overline{\mathrm{B}^0} \to f_{CP}}} = D \sin 2\beta\ \sin(\Delta m_q\, t)$$

Use large flavor sample to determine dilution *D* and resolution functions

Transfer knowledge to significanlty smaller *CP* sample

Same idea applies to Tevatron

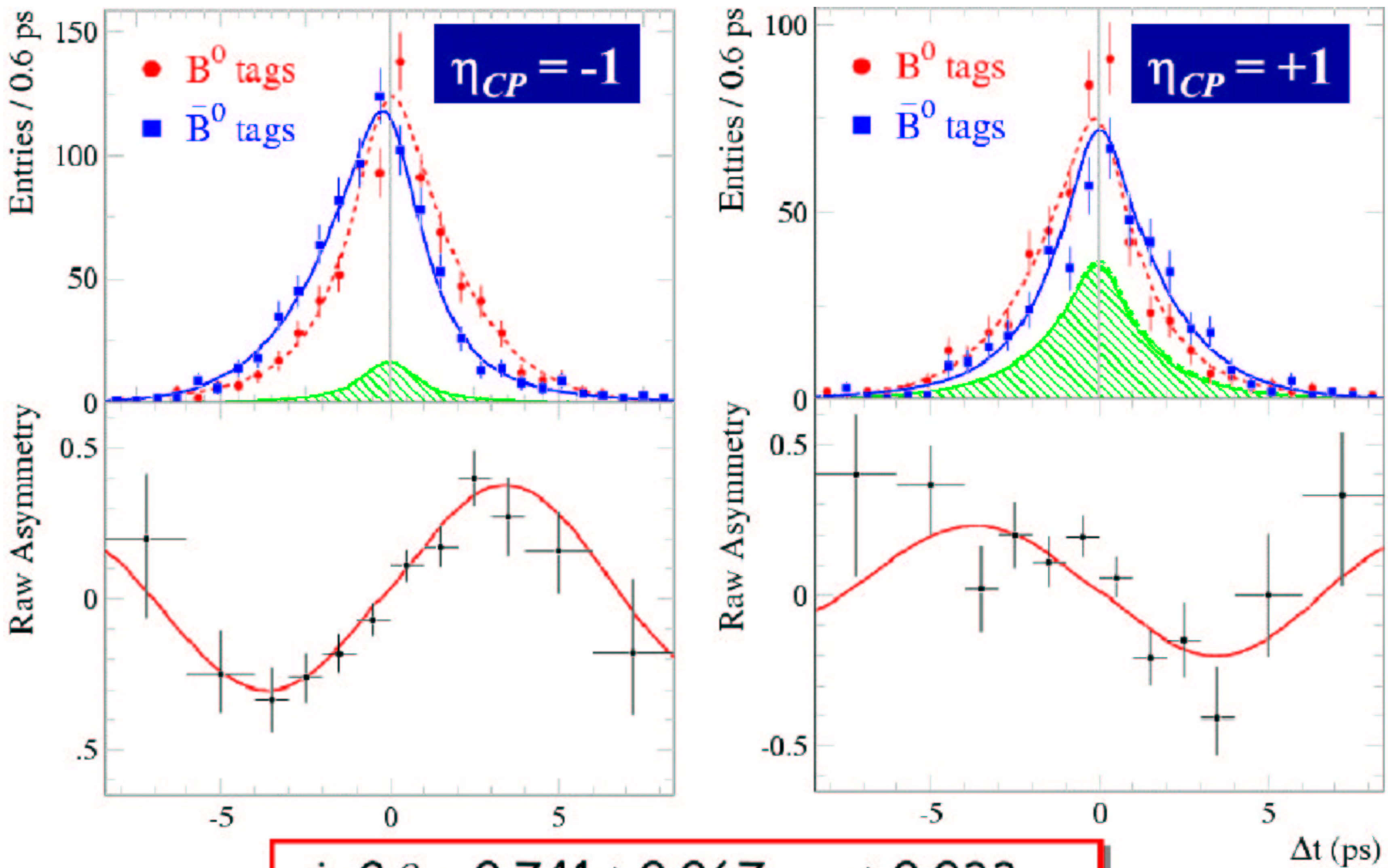
Essential Tests of Taggers



***CP* vs B_{flav} sample** — **B_{flav} sample vs MC**

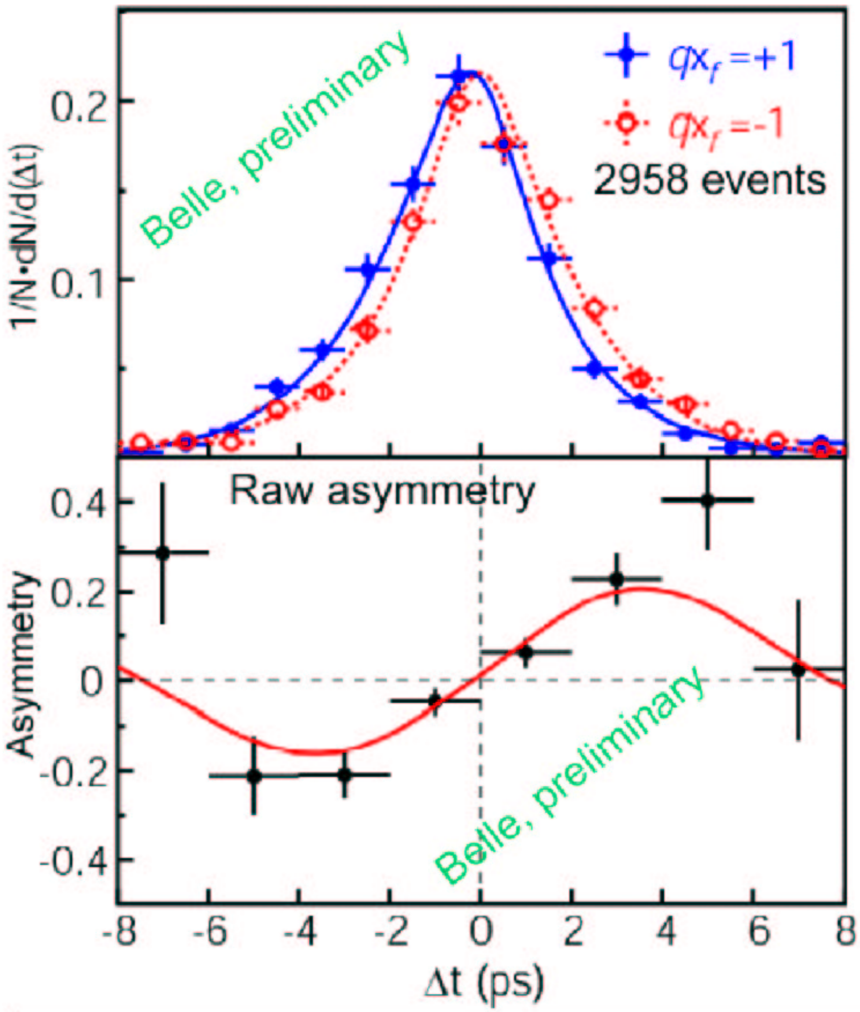
Crucial question: Does the tagger output look the same for the flavor and for the *CP* samples? Yes it does!

BaBar Result for $\sin 2\beta$



$$\sin 2\beta = 0.741 \pm 0.067_{(stat)} \pm 0.033_{(syst)}$$

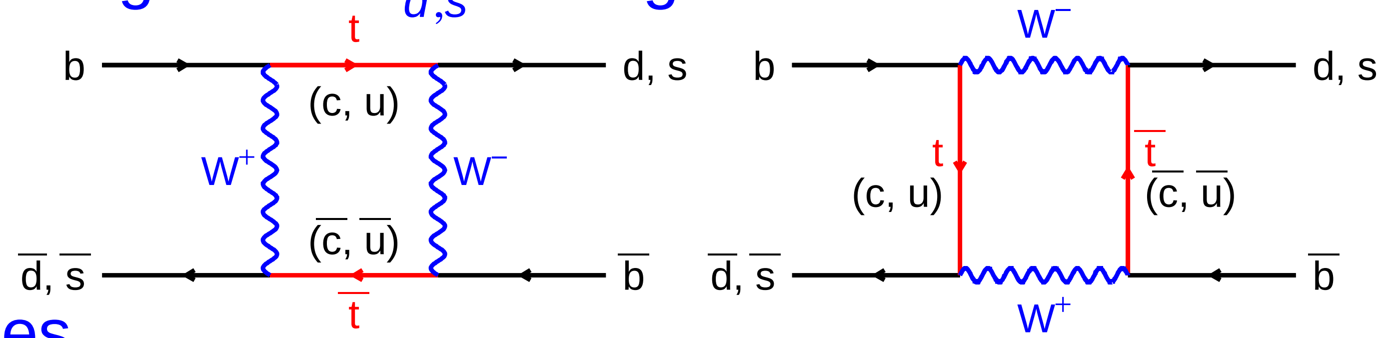
Belle Result for $\sin 2\beta$



$$\sin 2\beta = 0.719 \pm 0.074_{(stat)} \pm 0.035_{(syst)}$$

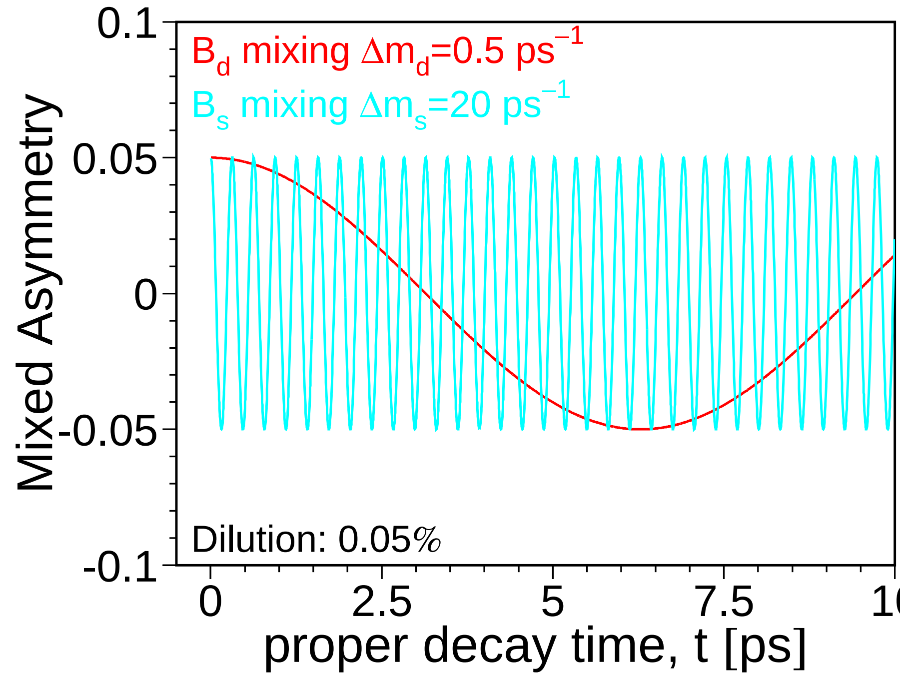
What is different for B_s Mixing?

Feynman diagram of $B^0_{d,s}$ mixing:



Differences

+ B^0_d crosses two families
+ B^0_s crosses one family
+ faster B^0_s mixing (≈ 40)



Experimental challenge

+ *ct* resolution critical
+ required resolution $\approx$ 50 fs
+ fully hadronic decays:
  $B_s \to D_s^- \pi^+ (\pi^+ \pi^-)$
+ hadronic trigger (SVT)
+ Kaon identification (TOF)

Where are we in CDF with B_s Mixing?

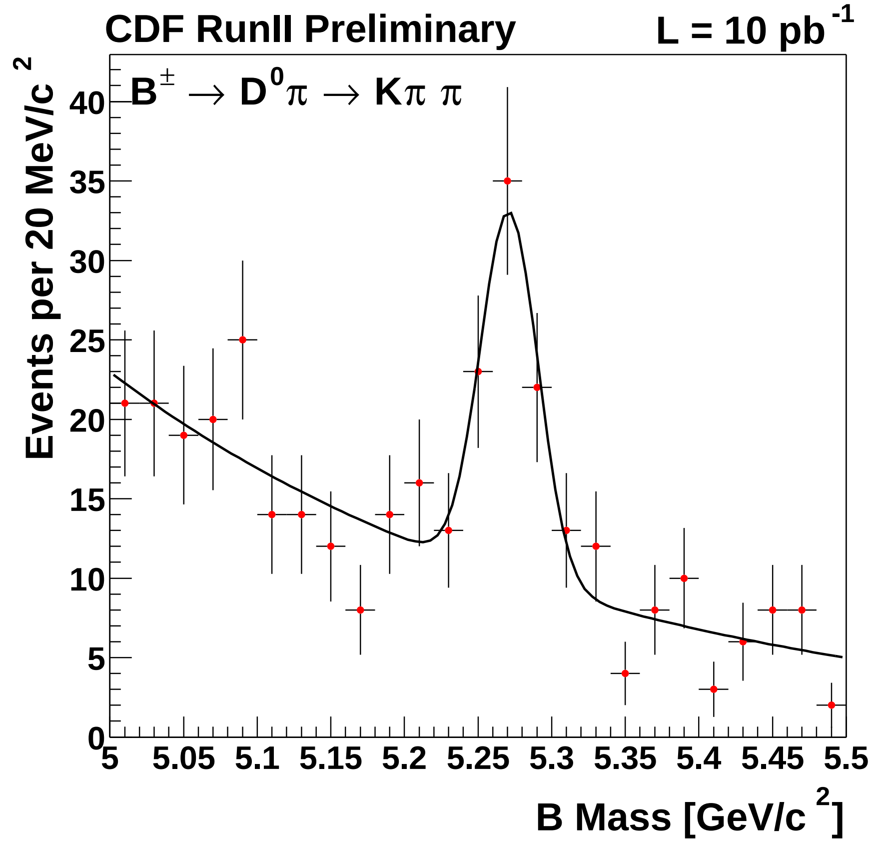
Hadronic trigger

- reasonably understood
- reached design resolution

  $\sigma(d_0) = 48\ \mu\mathrm{m}$
- not as efficient as planned

Offline tracking

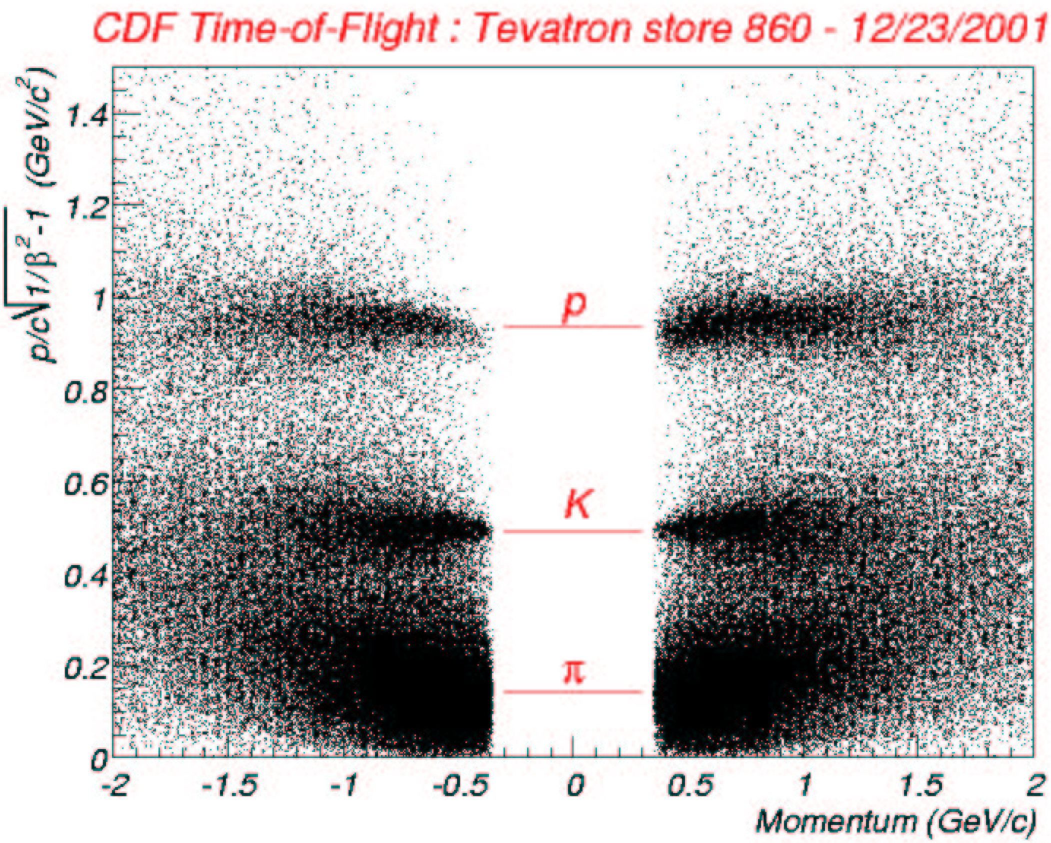
- r-ϕ well understood
- z tracking almost ready
- essential L00 not yet used



Where are we in CDF with B_s Mixing?

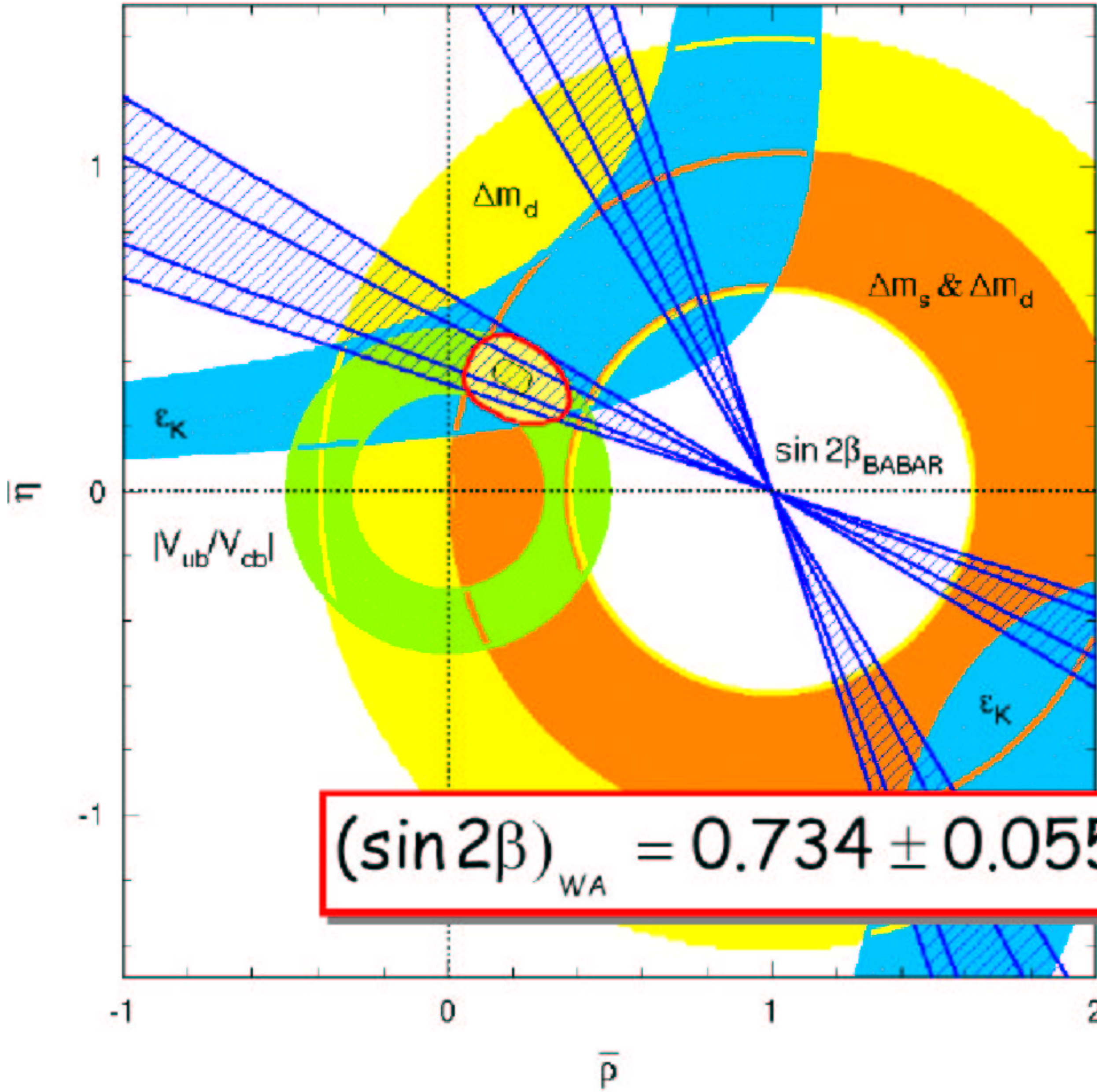
Particle Id

+ TOF hardware works well; resolution per PMT as expected
+ efficiency lower than expected; too many hits per bar



First B_s mixing results not earlier than summer 2004

Standard Model Constraints



$$(\sin 2\beta)_{WA} = 0.734 \pm 0.055 \ (stat+syst)$$

Conclusions

Physics Motivation

+ *CKM* physics exciting: potential discrepancy with SM
+ amount of *CP* violation well predicted but too small
+ additional measurements test consistency of SM

Comparison of $\Upsilon(4S)$ and $p\bar{p}$

+ beautifully complementary programs
+ high precision B^0, B^+ at the *B* Factories
+ all other *b* hadrons at Tevatron

Results

+ *CP* violation has been observed in *B* system
+ Era of precision *CKM* has started
+ consistent with expectations
+ lots of other *B* physics: spectroscopy $B_s, B_c, \Lambda_b, B^{**}$ ..